TENSILE RUPTURE STRENGTH OF SINGLE-BOLT CONNECTIONS IN PULTRUDED STRUCTURES

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TENSILE RUPTURE STRENGTH OF SINGLE-BOLT CONNECTIONS IN PULTRUDED STRUCTURES

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LIST OF SYMBOLS AND ABBREVIATIONS

θ The angle between applied force and fiber roving orientation used to classify fiber orientation as longitudinal or transverse

Θ Geometric reduction factor based on the ratio of end distance to effective width

Φ Resistance reduction factor that is equivalent to 0.5

A_e Effective area of a section

A_n Net area of a section

C_L Correlation coefficient for load in the longitudinal direction of pultruded material

C_T Correlation coefficient for load in the transverse direction of pultruded material

d_n Nominal hole diameter taken as the diameter of the bolt plus 1/16 in.

e_1 End distance

e_2 Edge distance

$F_L{}^t$ Characteristic value of the tensile strength in the longitudinal direction of the pultruded material, adjusted for end-use conditions

$F_T{}^t$ Characteristic value of the tensile strength in the transverse direction of the pultruded material, adjusted for end-use conditions

F_{oh}^t Open-hole tensile strength

g Gage spacing

k_{tc} Orthotropic material stress concentration factor

k_{te} Isotropic material stress concentration factor

$K_{nt,L}$ Net tension stress concentration factor in longitudinal material direction for a filled hole

$K_{nt,T}$ Net tension stress concentration factor in transverse material direction for a filled hole

n Number of bolts across the effective width

R_n	Nominal net tension strength adjusted for end use condition
ΦR_n	Net tension rupture design strength for a bolted connection
s	Pitch spacing
S_{pr}	Geometric ratio; w/d or g/d
t	Material thickness
w	Effective width

SUMMARY

This thesis presents a simplified design approach to estimate the tensile rupture strength of single-bolt connections in pultruded structures similar to those of civil engineering metallic structures. The proposed design equation allows the engineer to estimate the net-section tensile strength based on the connection geometry and the tensile material strength from the literature or manufacturer's data, if measured according to ASTM D5766. The work is supported by results of 60 existing single-bolt connection tests subjected to tensile loading and conducting 27 new tests. The proposed approach can be readily integrated into design practice as a substitute for the current approach in the ASCE Pre-Standard (2010).

CHAPTER 1. INTRODUCTION

The American Society of Civil Engineer's current Pre-Standard is the state-of-the-art practice for the structural design of fiber-reinforced polymers. For single-bolt connections subjected to tensile loading, the design strength based on the tensile rupture limit state follows a unique methodology tailored for aerospace applications. This work examines the existing ASCE Pre-standard approach for calculating the net section tensile rupture strength and proposes a simplified approach in line with those of civil engineering metallic structures, which have been in existence for over a century.

1.1 ASCE Pre-Standard

In 2010, the American Society of Civil Engineers published a document entitled "ASCE Pre-Standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer" (ASCE 2010). This document, referred to hereafter as "ASCE Pre-Standard," served as a proposed outline document for a consensus-based standard following a formal process (ASCE 2016)[1] . Irrespective of the pultruded structural element cross-section, design equations for computing the tensile rupture strength are based on a strength model of a flat plate containing the following:

1. A maximum of three bolts in a line that is parallel to the direction of the connection force, and/or maximum of three bolts in a single line with the connection force acting perpendicular to the line of bolting.

[1] ASCE (2016). ASCE Rules for Standards Committees, https://www.asce.org/uploadedFiles/Technical_Areas/Codes_and_Standards/asce-rules-standards-committees.pdf

2. A maximum of three “rows of bolts,” each of which contains no more than three bolts.

The definition of a “row of bolts” is given only in Section C8.2.5 of the ASCE Commentary, defined as “two or more bolts across the width of the connection component,” which corresponds to the direction perpendicular to that of the connection force axis.

Figure 1.1 illustrates the bolt configurations for which the equations for calculating the tensile rupture strength in the net section apply. For bolt arrangements, other than those of Figure 1.1, strengths must be determined by testing in accordance with Section 2.3.2 of the Pre-Standard. In this thesis, a connection with a single bolt (Figure 1.1a) is addressed.

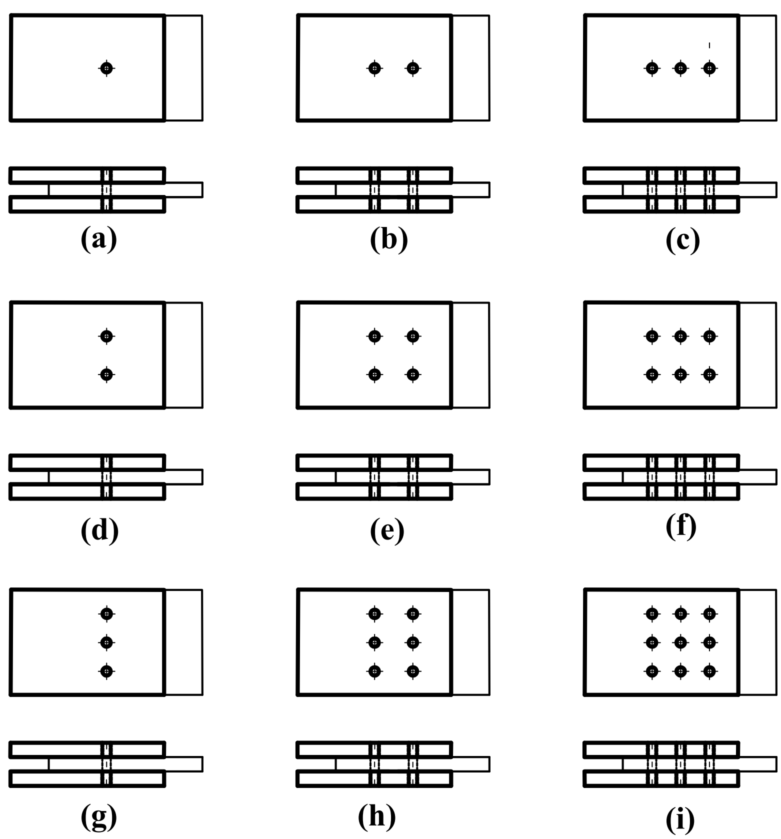


Figure 1.1 - Bolt Arrangements Covered by ASCE Pre-Standard Equations

1.2 Connection Modes of Failure

Under tensile loading, a fiber reinforced polymer composite connection fails in one of several modes that include:

1. Net tension,
2. Bearing on the bolt hole,
3. Combined tension and shear-out, and
4. Shear in the bolts.

The work presented in this thesis is limited to the net tension failure mode illustrated in Figure 1.2.

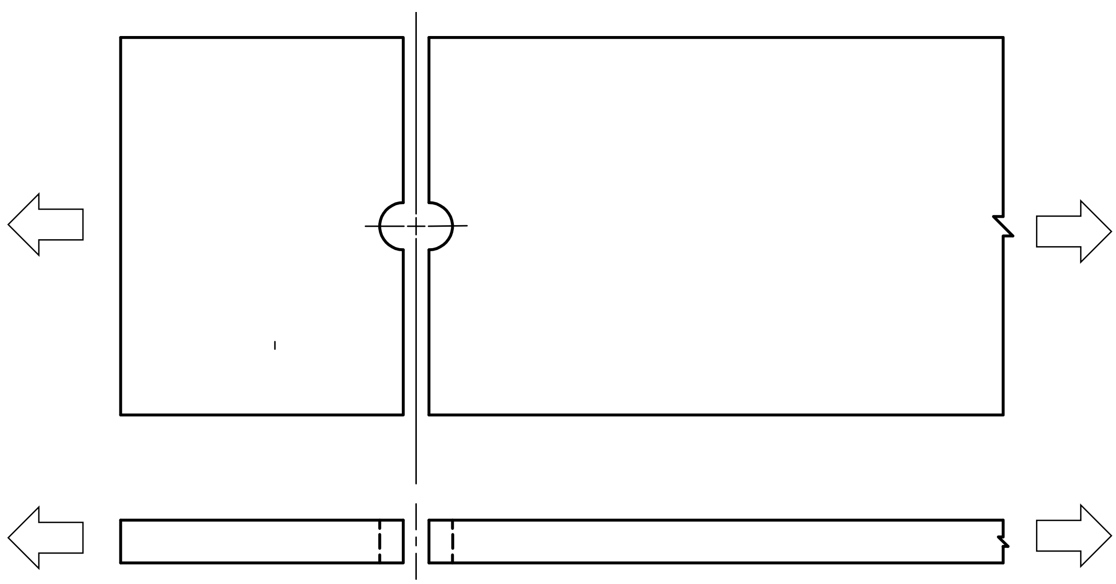


Figure 1.2 – Schematic of Net-Tension Failure

1.3 Calculation of Net-Section Tensile Strength for Bolted Pultruded Connections

For a bolted, pultruded plate connection, let *n* be the number of bolts across the effective width, *w*, of the plate. The tensile rupture strength can be determined from

Sections 8.3.3.2 and 8.3.2.4 of the ASCE Pre-Standard (2010) ϕR_{nt}, where ϕ and R_{nt} are the resistance factor and the net-tensile rupture strength, respectively, defined as follows:

$$\phi = \begin{cases} 0.5 & \text{for one "bolt row"} \\ 0.45 & \text{for two or three "bolt rows"} \end{cases} \tag{1.1}$$

$$R_{nt} = \begin{cases} \dfrac{(w - nd_n)tF_i{}^t}{K_{nt,i}} & \text{for one “bolt row”} \\ \dfrac{wtF_i{}^t}{K_{nt,i}L_{br}\left(\dfrac{w}{nd}\right) + \dfrac{K_{op,i}(1 - L_{br})}{1 - n\left(\dfrac{d_n}{w}\right)}} & \text{for two or three “bolt rows”} \end{cases} \tag{1.2}$$

where

$$w = \begin{cases} e_2 + e_2 & \text{for } n = 1 \\ e_2 + e_2 + (n-1)g & \text{for } n = 2 \text{ and } 3 \end{cases} \tag{1.3}$$

$$K_{nt,i} = \begin{cases} C_i\left[S_{pr} - 1.5\dfrac{(S_{pr} - 1)}{(S_{pr} + 1)}\Theta\right] + 1 & \text{for one “row”} \\ \dfrac{\left[C_i\left[S_{pr} - 1.5\dfrac{(S_{pr} - 1)}{(S_{pr} + 1)}\Theta\right] + 1\right]}{\dfrac{w}{nd} - 1} & \text{for two or three “rows”} \end{cases} \tag{1.4}$$

$$K_{op,i} = 1 + \mathrm{C_{op,i}}\left[1 + \left(1 - \frac{1}{S_{pr}}\right)^3\right] \tag{1.5}$$

$$\Theta = \begin{cases} 1.5 - 0.5\dfrac{w}{e_1} \quad \text{for} \quad \dfrac{e_1}{w} < 1 & \text{when n} = 1 \\ 1 \quad \text{for} \quad \dfrac{e_1}{w} \geq 1 & \text{when n} = 1 \\ 1.5 - 0.5\dfrac{g}{e_1} \quad \text{for} \quad \dfrac{e_1}{g} < 1 & \text{when n} = 2 \text{ or } 3 \\ 1 \quad \text{for} \quad \dfrac{e_1}{g} \geq 1 & \text{when n} = 2 \text{ or } 3 \end{cases} \tag{1.6}$$

$$S_{pr} = \begin{cases} \dfrac{w}{d} & \text{for n} = 1 \\ \dfrac{g}{d} & \text{for n} = 2 \text{ and } 3 \end{cases} \tag{1.7}$$

$$F_i^{\ t} = \begin{cases} F_L^{\ t} & \text{when } 0° \leq \theta \leq 5° \\ F_T^{\ t} & \text{when } 5° < \theta \leq 90° \end{cases} \tag{1.8}$$

where

θ = Angle between the direction of the force and the direction of roving in a connection, shown in Figure 1.3

d = Nominal bolt diameter

d_n = Bolt hole diameter taken as the bolt diameter plus 1/16 in.

$F_i^{\ t}$ = Tensile characteristic value

$K_{nt,i}$ = Non-linear tensile stress concentration factor

$K_{op,i}$ = Net tension stress concentration factor for an unfilled hole

n = Number of bolts in a bolt row

t = Thickness of a connected material

w = Effective width of a connection component

L_{br} = Proportion of the connection force taken in the bearing at the first "row"

S_{pr} = Geometric ratio for stress concentration

Θ = Geometric reduction coefficient for stress concentration factor

C_i = Non-linear stress distribution anisotropic-isotropic correlation coefficient, shown in Table 1.1 and 1.2

$C_{op,i}$ = Coefficient for bypass load in pultruded material

g = Gage spacing corresponding to the distance between the centerline of holes perpendicular to the line of forces

e_1 = End distance, distance between the loaded edge of a connection and the center of the nearest bolt hole, measurement is taken perpendicular to the bolt row orientation

e_2 = Edge distance, perpendicular distance from the center of the bolt to the edge adjacent to the loaded edge, measurement is taken parallel to the bolt row orientation

$$e_2 = \begin{cases} e_3 = e_4 = e_2 & \text{Connections with two equivalent side edges having a distance, } e_2 \\ e_3 = e_2, e_4 = e_{2min} & \text{Connections with two unequivalent side edges, having distances } e_2 \text{ and } 2e_{2min} \\ e_3 = e_4 = 2e_{2min} & \text{Connections with two equivalent side edges having a distance, } 2e_{2min} \end{cases} \quad (1.9)$$

$$C_{op,i} = 0.5 \quad \text{for pultruded strutural shape and plates} \quad (1.10)$$

Table 1.1 - Correlation Coefficient for Plate Connections

	θ	n=1	n=2 or 3
C_L	$0° \leq \theta \leq 5°$	0.4	0.4
C_T	$5° < \theta \leq 90°$	0.5	0.4

Table 1.2 - Correlation Coefficient for Shape Connections

	θ	n=1	n=2 or 3
C_L	$0° \leq \theta \leq 5°$	0.5	0.5
C_T	$5° < \theta \leq 90°$	0.5	0.5

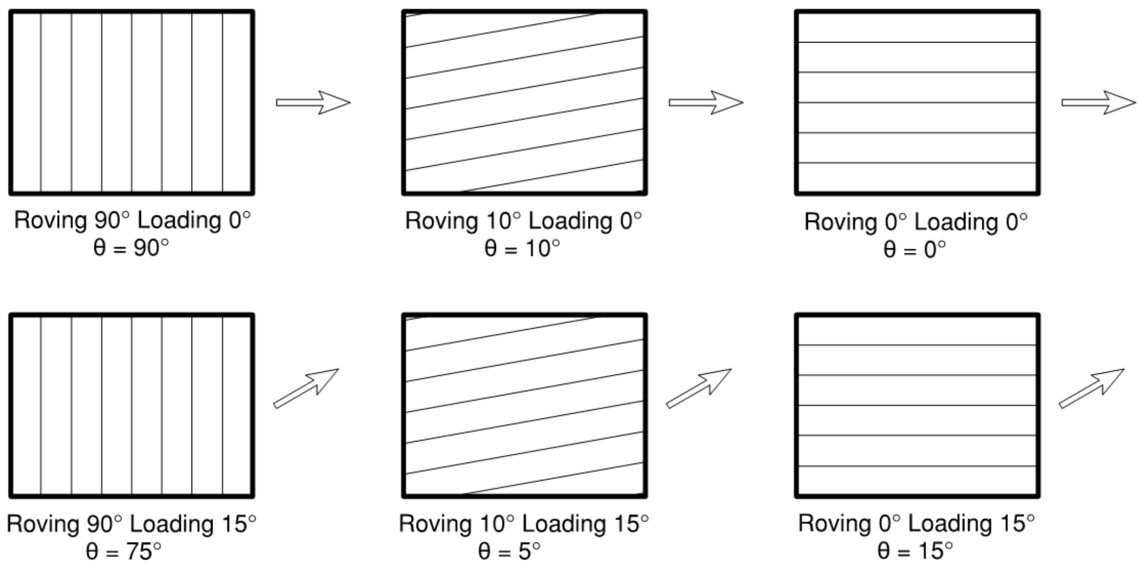


Figure 1.3 – Angle Between the Direction of the Force and the Direction of the Roving

An example illustrating the ASCE Pre-Standard (2010) method of calculating the tensile rupture strength of single-bolt connections in pultruded materials is given in Appendix A.1.

1.4 Basis of the ASCE Provisions Related to Net Tension

The design provisions for bolted connections were developed based on the research performed by Hart-Smith (1976). Hart-Smith (1976) tested graphite-epoxy, single-bolt connections, utilizing combinations of two different bolt diameters (0.19” and 0.25”), four different plate widths (2d, 3d, 4d, and 6d), and three different end distances (3d, 4d, and 6d).

The test specimen coupon geometries were chosen by Hart-Smith (1976) to trigger three basic failure modes: net-section tension failure through the bolt hole, bearing on the bolt hole, and shear-out. For the case of net-section failure, the strength of the single bolt connection is determined as follows:

$$P = \frac{(w-d)tF_{tu}}{k_{tc}} \tag{1.11}$$

$$k_{tc} = 1 + C(k_{te} - 1) \tag{1.12}$$

$$k_{te} = 2 + \left(\frac{w}{d} - 1\right) - 1.5\frac{\left(\frac{w}{d} - 1\right)}{\left(\frac{w}{d} + 1\right)}\theta \tag{1.13}$$

$$\Theta = \{1.5 - 0.5\frac{w}{e_1} \quad for \quad \frac{e_1}{w} < 1 \; 1 \quad for \quad \frac{e_1}{w} \geq 1 \tag{1.14}$$

Where

Θ = Coefficient

C = Constant

d = Bolt diameter

e_1 = Edge distance from middle of bolt

F_{tu} = Material allowable tensile ultimate strength

k_{tc} = Composite stress concentration factor at failure, with respect to net section tension stress

k_{te} = elastic isotropic stress concentration factor, with respect to net section tension stress

P = Load at failure

t = Laminate thickness

w = Specimen width

Hart-Smith's (1976) empirical method was used by Rosner (1992) to examine the tensile strength of single-bolt joints in pultruded materials. Rosner (1992) conducted experiments on 102 single-bolt connections having a double shear lap configuration, with a nominal bolt and hole diameters of 0.75" and 0.8125", respectively, as shown in Figure 1.4. The material tensile strengths were determined from tests conducted according to ASTM D638.

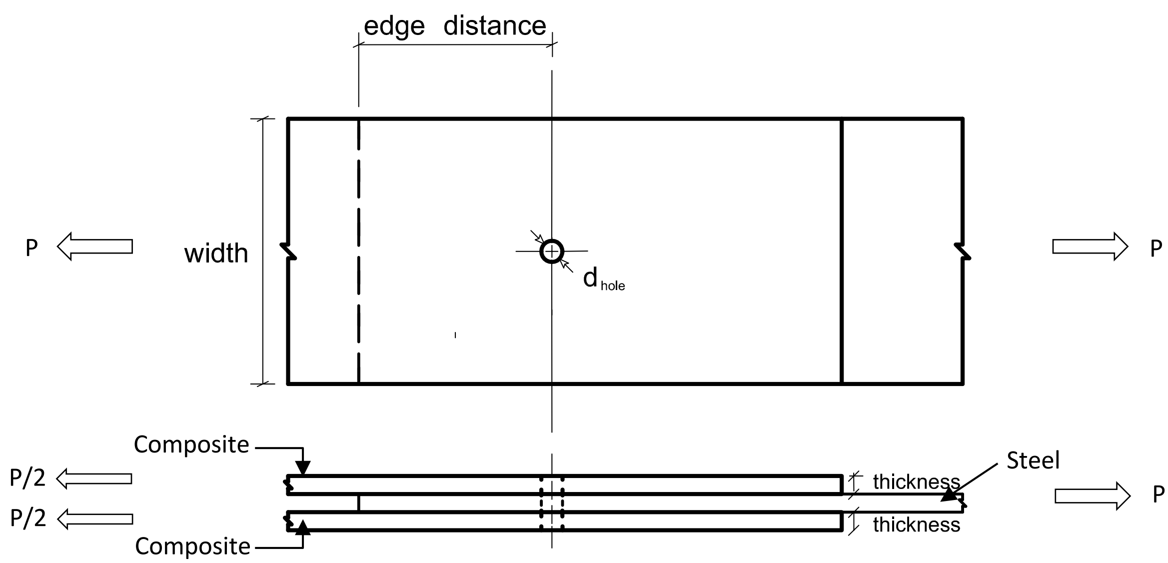


Figure 1.4 – Rosner's Test Arrangement

In the experimental program, Rosner (1992) considered four basic geometric parameters. These are (1) width of the plate: 1" to 10", (2) bolt-hole edge distance: 0.75" to 8", (3) plate thickness of the member: 0.375", 0.50", and 0.75", and (4) orientation of the roving direction with respect to the applied load. When calculating the stress concentration factor k_{te}, for an isotropic material, Rosner (1992) proposed to modify slightly the non-dimensional parameter, Θ, (Equation 1.14) necessary to compute the isotropic stress concentration factor (Equation 1.13) proposed by Hart-Smith (1976), in the form

$$\Theta = 1.5 - 0.5\frac{w}{e_1} \; for \; \frac{e_1}{w} > 0 \tag{1.15}$$

where

e_1 = Edge distance from middle of bolt

w = Width of connection member

It should be noted that, for all of Rosner's tests specimens that exhibited net-section tension failure, the values of k_{te} computed from Equation 1.13 and 1.15 do not differ significantly from those computed from Equation 1.13 and 1.14. This is illustrated in Figure 1.5.

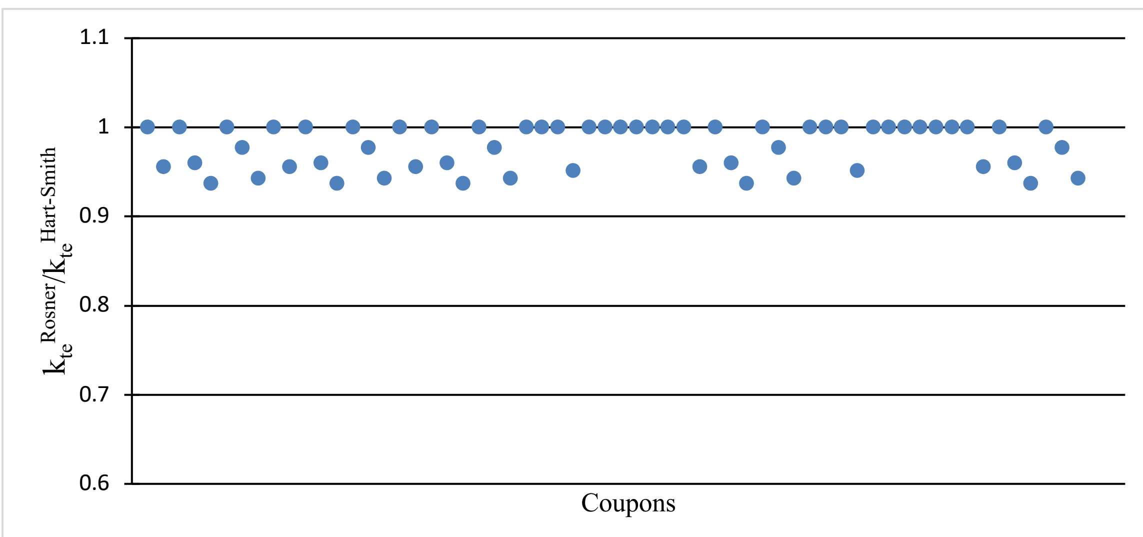


Figure 1.5 - Ratio of k_{te} Calculated by Rosner's Proposed Θ and Hart-Smith's Proposed Θ

CHAPTER 2. ANALYSES OF ROSNER EXPERIMENTAL DATA

This chapter comprises analyses conducted to examine the results of experiments performed by Rosner (1992) on double-lap single-bolted connections made of pultruded materials. The experimental data are analyzed to compute the ratios of the connection experimentally observed strength to that computed, accordingly to the approach developed by Hart-Smith (1976). The experimental strengths of the connections are then compared with values computed from a set of equations adopted in the ASCE Pre-Standard (2010). The purposes of these analyses are to:

1. Independently analyze the experimental data reported by Rosner (1992), and
2. Examine if the use of the bolt hole diameter as opposed to the bolt diameter will have significant effects on predicting single-bolt connection strengths in pultruded structures.

2.1 Single Bolted Connection Tests (Rosner 1992)

The pultruded material connection test data of Rosner (1992) are presented in Table B.1. The data include the geometrical parameters of the tests (e.g., width of the plate, bolt-hole edge distance, plate thickness of the member, and orientation of the roving direction with respect to the applied load), the material tensile strength determined in accordance with ASTM D638, and the connection tensile load at failure.

2.2 Experimental Data Analyses

The experimental data of Rosner (1992) are evaluated analytically by means of both the Hart-Smith's (1976) empirical method and the recommended design formulae of the ASCE Pre-Standard (2010).

Regarding the Hart-Smith empirical approach, the connection tensile rupture strengths of Rosner's experiment first are calculated by Equation 1.11, where the net tension area is defined as the connection gross area minus the diameter of the bolt. This is done to be consistent with the expression developed by Hart-Smith (1976) whose experiments were conducted on single-bolted joints with tight hole clearances (close-fit condition). The tensile rupture strengths for Rosner's tests are calculated using the same Equation 1.11 but after replacing the diameter of the bolt with that of the hole. Thus, the joint net area is defined as the joint gross area minus the hole diameter. The results of these calculations are presented in Tables 2.1, 2.2, and 2.3, where the composite stress concentration factor k_{tc}, the calculated isotropic stress concentration factor k_{te}, and the anisotropic-isotropic correlation coefficient, C, are shown. Also shown in these tables is the coefficient C_{design} that corresponds to the slope of the best-fit line of the set of data having the coordinates (k_{te}-1) and (k_{tc}-1) for each set of experiments having the same thickness, bolt diameter, hole diameter, and fiber orientation. This coefficient C_{design} is used to calculate the predicted tensile rupture strength $P_{calc.}$

Based on results presented in Tables 2.1, 2.2, and 2.3, there does not appear to be a significant difference in the P_{exp}/P_{calc} values when using either the diameter of the bolt or the diameter of the hole. Calculated values using the bolt hole or bolt diameters will yield practically similar results, which shows that it does not matter which is used. The use of the nominal hole diameter is common is civil engineering design equations while the use of nominal bolt diameter is common in aerospace design practice.

The results of the calculations performed on Rosner's test results using design formulae outlined in the ASCE Pre-Standard (2010) Provisions are presented in Tables 2.4, 2.5, and 2.6. The C values proposed by ASCE Pre-Standard (2010), for single bolt connections, are 0.4 and 0.5 when the connection force is applied in the longitudinal (roving) and transverse (perpendicular to the roving) directions, respectively. C depends on the bolt diameter, plate thickness, and the FRP material properties; if C is 1.0, then the material is considered to be perfectly brittle and if C is zero, then the material is considered to be perfectly plastic (Hart-Smith 1987).

The correlation coefficients, C, resulting from analyzing Rosner's test data are calculated in this work to be 0.44, 0.36, and 0.35, for tests with loads applied in the longitudinal, transverse, and in the 45-degree direction, respectively. These values differ from those reported from Rosner (1992) as 0.33, 0.25, and 0.2. From Rosner's (2010) study, it is not clear how Rosner computed the reported values of C. The lower C values reported by Rosner indicate that the pultruded plates used in the connection tests were less brittle than what they actually were.

In Table 2.7 and Figures 2.1 - 2.3, the values of P_{exp}/P_{calc} are shown for Rosner's test results, when C is equal to 0, 0.4, 0.5, and 1. The computations in this thesis indicate that as C increases, P_{calc} decreases. Using 0.5, as opposed to the suggested values of 0.4 or 0.5, generally yields a lower estimate of P_{calc}, which may be appropriate at this time until additional experimental data becomes available.

Furthermore, when computing the area of the net section in the Hart-Smith empirical method, deducting the area of the bolt hole, as opposed to the area of the bolt, will yield negligible difference in calculating the strength of a single-bolt connection in pultruded structures when the bolt hole clearance is 1/16" as commonly adopted in civil engineering design practice.

Table 2.1 - Analyses of Rosner's Experimental Tests: Forces Applied in the Longitudinal Direction – 0°

COUPON	$d = d_{bolt}$						$d = d_{hole}$					
	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{\exp}}{P_{cal}}$	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{\exp}}{P_{cal}}$
A1	1.96	2.15	0.83	0.53	3341	0.82	1.47	2.15	0.40	0.42	2711	1.01
A2	1.66	2.12	0.59		3380	0.96	1.24	2.12	0.22		2739	1.19
A3	1.63	2.50	0.42		9001	1.10	1.49	2.50	0.33		9051	1.09
A4	1.64	2.50	0.43		9001	1.09	1.50	2.50	0.33		9051	1.09
A5	1.82	2.50	0.55		9001	0.98	1.67	2.50	0.45		9051	0.98
A6	2.17	3.10	0.56		1275	0.97	2.06	3.10	0.50		13537	0.92
A7	2.07	2.98	0.54		13125	0.99	1.97	2.98	0.49		13890	0.94
A8	1.95	2.98	0.48		13125	1.05	1.86	2.98	0.43		13890	0.99
Coupons A1-A8 have a thickness t = 0.38" Nominal bolt diameter: d_{bolt}= ¾"					Avg SD COV	1.0 0.09 0.09	Nominal bolt hole diam. $D_h = d_b$ +1/16"				Avg SD COV	1.03 0.09 0.09
B1	2.01	2.15	0.87	0.40	4135	0.73	1.51	2.15	0.44	0.30	3367	0.89
B2	1.80	2.12	0.71		4176	0.80	1.35	2.12	0.31		3394	0.99
B3	1.54	2.50	0.36		11342	1.04	1.41	2.50	0.27		11471	1.02
B4	1.33	2.50	0.22		11342	1.20	1.22	2.50	0.15		11471	1.19
B5	1.46	2.50	0.31		11342	1.09	1.34	2.50	0.23		11471	1.08
B6	1.84	3.10	0.40		16457	1.00	1.75	3.10	0.36		17646	0.93
B7	1.78	2.98	0.39		16871	1.00	1.69	2.98	0.35		18021	0.94
B8	1.61	2.98	0.31		16871	1.11	1.53	2.98	0.27		18021	1.04
Coupons B1-B8 have a thickness: t = 0.50" Nominal bolt diameter: d_{bolt}= ¾"					Avg SD COV	1.00 0.16 0.16	Nominal bolt hole diam. $D_h = d_b$ +1/16"				Avg SD COV	1.01 0.09 0.09
E1	2.15	0.75	0.84	0.39	6267	0.73	1.48	2.15	0.42	0.29	5060	0.91
E2	2.12	8.00	0.64		6329	0.83	1.29	2.12	0.26		5100	1.03
E3	2.50	1.00	0.38		17228	1.00	1.44	2.50	0.29		17245	1.00
E4	2.50	1.67	0.29		17228	1.10	1.32	2.50	0.21		17245	1.09
E5	2.50	2.67	0.29		17228	1.10	1.32	2.50	0.21		17245	1.10
E6	3.10	0.75	0.43		25067	0.95	1.80	3.10	0.38		26545	0.90
E7	2.98	1.25	0.36		25687	1.03	1.63	2.98	0.32		27105	0.97
E8	2.98	2.00	0.28		25687	1.13	1.47	2.98	0.24		27105	1.08
Coupons E1-E8 have a thickness: t = 0.75" Nominal bolt diameter: dbolt= ¾"					Avg SD COV	0.98 0.14 0.14	Nominal bolt hole diam. $D_h = d_b$ +1/16"				Avg SD COV	1.01 0.08 0.08

Table 2.2 - Analyses of Rosner's Experimental Tests: Applied in the Transverse Direction – 90°

COUPON	$d = d_{bolt}$						$d = d_{hole}$					
	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$
C1	1.51	2.15	0.44		2813	0.94	1.13	2.15	0.11		2121	1.25
C2	1.52	2.12	0.47		2839	0.93	1.14	2.15	0.13		2140	1.23
C3	1.53	2.50	0.35		7752	1.01	1.40	2.12	0.27		7151	1.10
C4	1.86	2.50	0.57		7752	0.83	1.71	2.50	0.47		7151	0.90
C5	1.66	2.50	0.44		7752	0.93	1.53	2.50	0.35		7151	1.01
C6	1.54	3.10	0.26		11321	1.15	1.46	2.50	0.22		10838	1.20
C7	1.74	2.98	0.37		11594	0.99	1.65	3.10	0.33		11096	1.04
C8	1.46	2.98	0.23		11594	1.18	1.39	2.98	0.20		11096	1.23
C9	2.93	6.16	0.37	0.37	18019	0.98	2.88	2.98	0.36	0.36	17878	0.99
C10	2.85	5.61	0.40		19361	0.94	2.79	6.16	0.39		19200	0.95
C11	2.18	5.31	0.27		20207	1.18	2.13	5.61	0.26		20033	1.19
C12	2.15	5.31	0.27		20207	1.20	2.11	5.31	0.26		20033	1.21
C13	4.51	9.58	0.41		20312	0.92	4.46	5.31	0.40		20340	0.92
C14	4.14	8.65	0.41		22137	0.92	4.09	9.58	0.40		22159	0.92
C15	3.10	8.13	0.30		23315	1.16	3.07	8.65	0.29		23333	1.16
C17	7.81	16.70	0.43		21975	0.86	7.76	8.13	0.43		22157	0.85
C18	5.77	14.98	0.34		24237	1.06	5.73	16.70	0.34		24431	1.05
C19	4.85	14.01	0.30		25727	1.19	4.81	14.98	0.29		25928	1.18
Coupons C1-C19 have a thickness t = 0.50" Nominal bolt diameter: d_{bolt}= ¾"					Avg	1.06	Nominal bolt hole diam. $D_h = d_b + 1/16$"				Avg	1.06
					SD	0.14					SD	0.15
					COV	0.13					COV	0.14

Table 2.3 - Analyses of Rosner's Experimental Tests: Forces Applied in the 45° Direction

COUPON	$d = d_{bolt}$						$d = d_{hole}$					
	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$
D1	2.15	0.75	0.57	0.35	3020	0.85	1.24	2.15	0.21	0.35	2277	1.13
D2	2.12	8.00	0.57		3047	0.85	1.23	2.12	0.20		2297	1.13
D3	2.50	1.00	0.27		8338	1.08	1.29	2.50	0.20		7690	1.18
D4	2.50	1.67	0.55		8338	0.84	1.68	2.50	0.45		7690	0.91
D5	2.50	2.67	0.21		8338	1.17	1.20	2.50	0.13		7690	1.27
D6	3.10	0.75	0.22		12210	1.19	1.38	3.10	0.18		11689	1.25
D7	2.98	1.25	0.49		12498	0.86	1.88	2.98	0.44		11961	0.90
D8	2.98	2.00	0.24		12498	1.15	1.40	2.98	0.20		11961	1.20
D9	6.16	0.38	0.40		19584	0.92	3.02	6.16	0.39		19431	0.92
D10	5.61	0.63	0.34		21022	1.03	2.50	5.61	0.32		20849	1.04
D11	5.31	1.00	0.26		21929	1.20	2.06	5.31	0.25		21741	1.21
D12	5.31	2.00	0.29		21929	1.13	2.20	5.31	0.28		21741	1.13
D13	9.58	0.25	0.40		22156	0.90	4.41	9.58	0.40		22190	0.90
D14	8.65	0.42	0.42		24129	0.87	4.18	8.65	0.42		24156	0.87
D15	8.13	0.67	0.25		25401	1.27	2.74	8.13	0.24		25423	1.27
D17	16.70	0.15	0.44		24049	0.83	7.78	16.70	0.43		24253	0.83
D18	14.98	0.25	0.32		26510	1.08	5.48	14.98	0.32		26728	1.07
D19	14.01	0.40	0.26		28130	1.26	4.41	14.01	0.26		28355	1.25
Coupons D1-D19 have a thickness t = 0.50" Nominal bolt diameter: d_{bolt}= ¾"					Avg	1.07	Nominal bolt hole diam. $D_h = d_b$ +1/16"				Avg	1.07
					SD	0.18					SD	0.18
					COV	0.17					COV	0.17

Table 2.4 - Application of ASCE Pre-Standard to Rosner's Experimental Data: Forces Applied in the Longitudinal Direction – 0°

COUPON	Θ	C	S_{pr}	K_{nt}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$
A1	0.83	0.4	1.33	1.46	3681	0.75
A2	1.00	0.4	1.33	1.45	3717	0.87
A3	1.00	0.4	2.00	1.60	10090	0.98
A4	1.00	0.4	2.00	1.60	10090	0.98
A5	1.00	0.4	2.00	1.60	10090	0.88
A6	0.83	0.4	2.67	1.84	14628	0.85
A7	1.00	0.4	2.67	1.79	14998	0.87
A8	1.00	0.4	2.67	1.79	14998	0.92
Coupons A1-A8 have a thickness					Avg	0.97
St = 0.38"					SD	0.08
Nominal bolt diameter: d_{bolt}= ¾"					COV	0.08
B1	0.83	0.4	1.33	1.46	4121	0.73
B2	1.00	0.4	1.33	1.45	4162	0.81
B3	1.00	0.4	2.00	1.60	11297	1.04
B4	1.00	0.4	2.00	1.60	11297	1.20
B5	1.00	0.4	2.00	1.60	11297	1.09
B6	0.83	0.4	2.67	1.84	16378	1.00
B7	1.00	0.4	2.67	1.79	16793	1.01
B8	1.00	0.4	2.67	1.79	16793	1.12
Coupons B1-B8 have a thickness:					Avg	1.10
t = 0.50"					SD	0.17
Nominal bolt diameter: d_{bolt}= ¾"					COV	0.15
E1	0.83	0.4	1.33	1.46	6182	0.74
E2	1.00	0.4	1.33	1.45	6243	0.84
E3	1.00	0.4	2.00	1.60	16945	1.02
E4	1.00	0.4	2.00	1.60	16945	1.11
E5	1.00	0.4	2.00	1.60	16945	1.12
E6	0.83	0.4	2.67	1.84	24567	0.97
E7	1.00	0.4	2.67	1.79	25189	1.05
E8	1.00	0.4	2.67	1.79	25189	1.16
Coupons E1-E8 have a thickness:					Avg	1.10
t = 0.75"					SD	0.16
Nominal bolt diameter: dbolt= ¾"					COV	0.15

Table 2.5 - Application of ASCE Pre-Standard to Rosner's Experimental Data: Forces Applied in the Transverse Direction – 90°

COUPON	Θ	C	S_{pr}	K_{nt}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$
C1	0.83	0.5	1.33	1.58	2536	1.05
C2	1.00	0.5	1.33	1.56	2565	1.03
C3	1.00	0.5	2.00	1.75	6857	1.14
C4	1.00	0.5	2.00	1.75	6857	0.94
C5	1.00	0.5	2.00	1.75	6857	1.05
C6	0.83	0.5	2.67	2.05	9760	1.33
C7	1.00	0.5	2.67	1.99	10038	1.15
C8	1.00	0.5	2.67	1.99	10038	1.36
C9	0.17	0.5	5.33	3.58	14521	1.22
C10	0.70	0.5	5.33	3.31	15722	1.16
C11	1.00	0.5	5.33	3.15	16490	1.45
C12	1.00	0.5	5.33	3.15	16490	1.47
C13	-0	0.5	8.00	5.29	15874	1.17
C14	0.30	0.5	8.00	4.83	17409	1.17
C15	0.75	0.5	8.00	4.56	18411	1.47
C17	-1.83	0.5	13.33	8.85	16724	1.13
C18	-0.50	0.5	13.33	7.99	18525	1.39
C19	0.25	0.5	13.33	7.51	19719	1.55
Coupons C1-C19 have a thickness					Avg	1.23
t = 0.50"					SD	0.17
Nominal bolt diameter: d_{bolt}= ¾"					COV	0.14

Table 2.6 - Application of ASCE Pre-Standard to Rosner's Experimental Data: Forces Applied in the 45° Direction

COUPON	Θ	C	S_{pr}	K_{nt}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$
D1	0.83	0.5	1.33	1.58	2694	0.95
D2	1.00	0.5	1.33	1.56	2725	0.95
D3	1.00	0.5	2.00	1.75	7286	1.24
D4	1.00	0.5	2.00	1.75	7286	0.96
D5	1.00	0.5	2.00	1.75	7286	1.34
D6	0.83	0.5	2.67	2.05	10370	1.41
D7	1.00	0.5	2.67	1.99	10665	1.09
D8	1.00	0.5	2.67	1.99	10665	1.35
D9	0.17	0.5	5.33	3.58	15428	1.16
D10	0.70	0.5	5.33	3.31	16705	1.30
D11	1.00	0.5	5.33	3.15	17520	1.50
D12	1.00	0.5	5.33	3.15	17520	1.41
D13	-0.50	0.5	8.00	5.29	16866	1.19
D14	0.30	0.5	8.00	4.83	18497	1.14
D15	0.75	0.5	8.00	4.56	19562	1.65
D17	-1.83	0.5	13.33	8.85	17769	1.13
D18	-0.50	0.5	13.33	7.99	19682	1.45
D19	0.25	0.5	13.33	7.51	20952	1.69
Coupons C1-C19 have a thickness					Avg	1.27
t = 0.50"					SD	0.22
Nominal bolt diameter: d_{bolt}= ¾"					COV	0.17

Table 2.7 - Variation of P_{exp}/P_{calc} for different values of Correlation Coefficient C

Roving Direction	P_{exp}/P_{calc}	C 0.0	0.4	0.5	1.0
Longitudinal	Average	0.59	0.96	1.06	1.52
	SD	0.07	0.13	0.15	0.25
	COV	0.12	0.14	0.14	0.16
Transverse	Average	0.44	1.08	1.23	2.03
	SD	0.19	0.13	0.17	0.45
	COV	0.43	0.12	0.14	0.22
Diagonal	Average	0.45	1.10	1.27	2.09
	SD	0.20	0.17	0.22	0.52
	COV	0.44	0.15	0.17	0.25

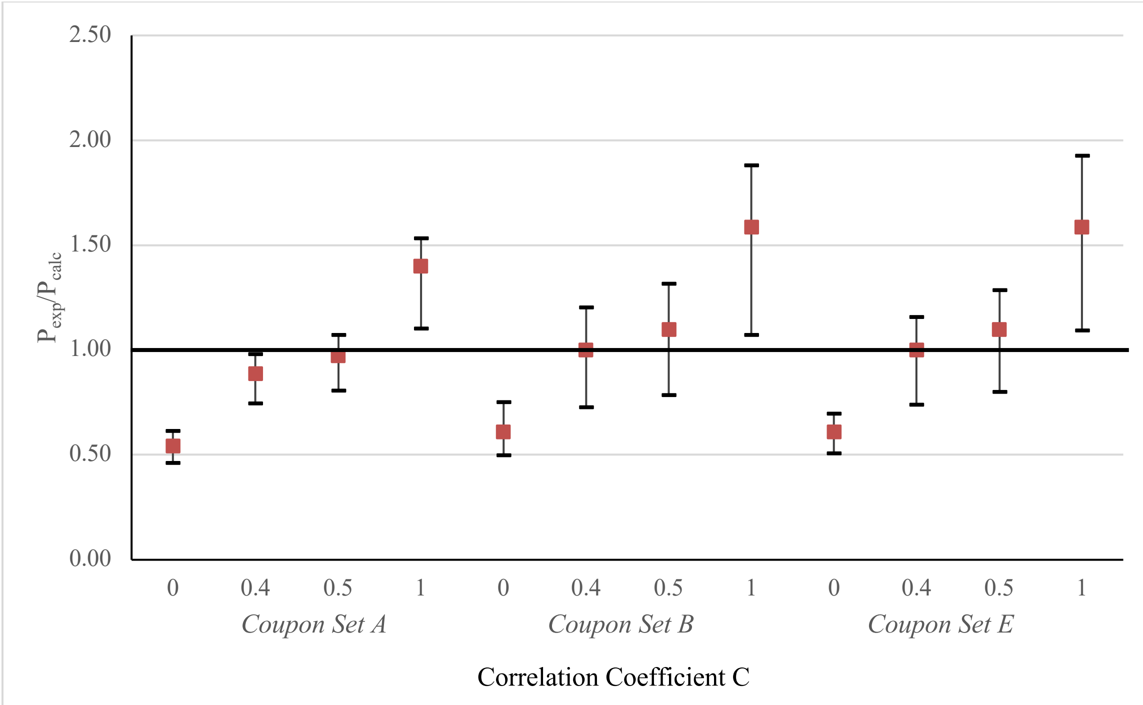


Figure 2.1 – P_{exp}/P_{calc} for Different Correlation Coefficients C: Forces Applied in the Longitudinal Direction – 0°

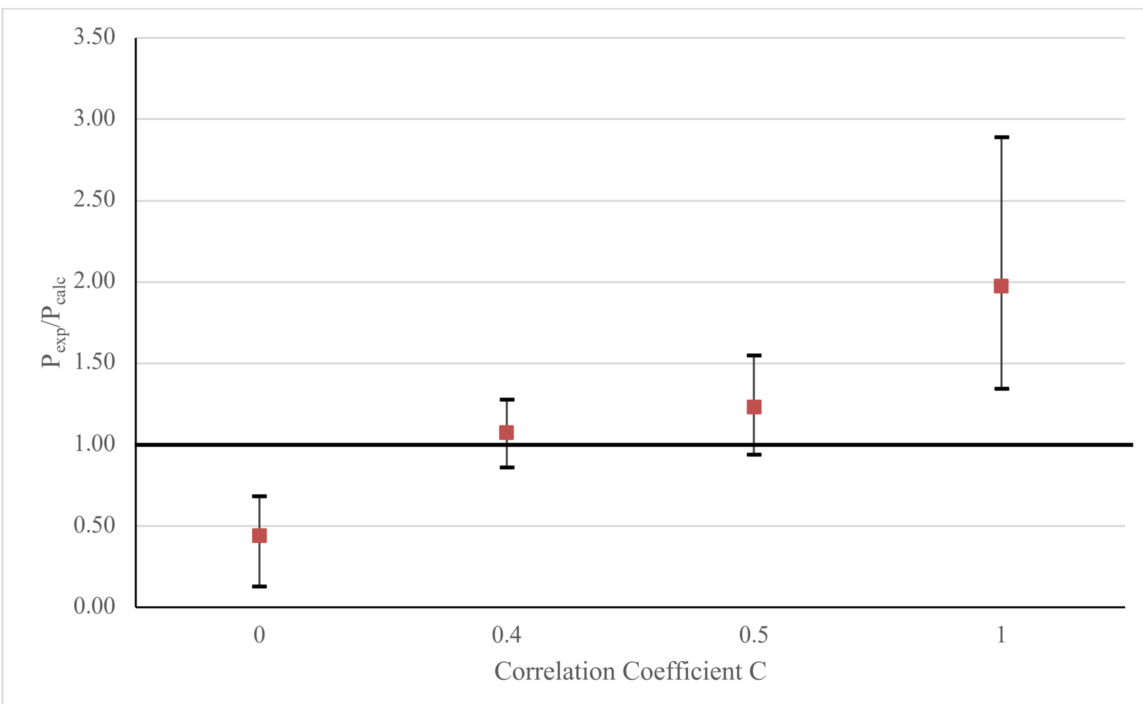


Figure 2.2 - P_{exp}/P_{calc} for Different Correlation Coefficients C: Forces Applied in the Transverse Direction – 90°

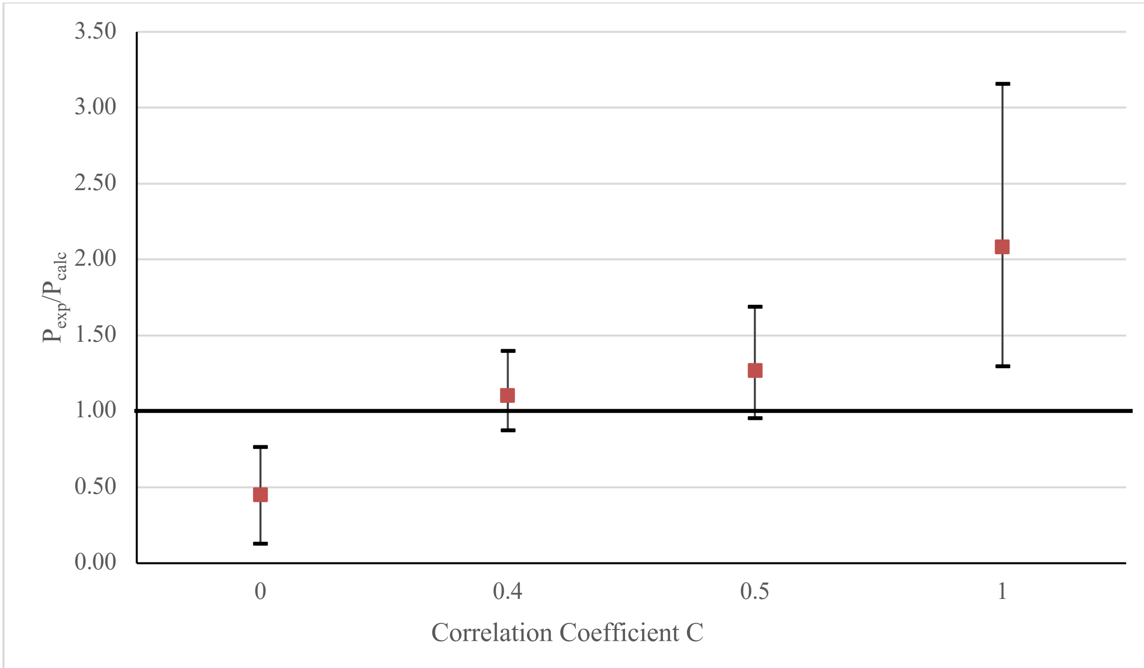


Figure 2.3 - P_{exp}/P_{calc} for Different Correlation Coefficients C: Forces Applied in the 45° Direction

CHAPTER 3. EXPERIMENTAL TEST PROGRAM AND RESULTS

This chapter presents the experiments conducted to support the proposed simplified equation to estimate the net tensile strength for single bolted connections. This equation is similar to that found in the AISC Specification for Structural Steel Buildings (ANSI/AISC 360-16), which can be expressed in the form:

$$R_n = A_n F^t \tag{3.1}$$

where, A_n is the net area of the connection member and F^t is the material tensile strength that needs to be determined. This proposed simplified approach is similar to that currently used in the design of metallic civil structural engineering structures.

3.1 Materials

A 4'x8' EXTREN™ 600 series plate manufactured by Morrison Molded Fiber Glass company (currently Strongwell) was used for this study. The plate was ¼" thick and was manufactured by the pultrusion process. The plate material consisted of Vinylester resin with flame retardant additive and UV inhibitor reinforced with E-glass rovings and E-glass continuous stand mats. The volume fractions of the E-glass reinforcement and of the matrix are approximately 35% and 65%, respectively.

3.2 Material Tensile Strength Testing

Using the material described, a total of 122 tensile test coupons having the dimensions specified in ASTM D638, ASTM D3039, and ASTM D5766 standards were cut from a plate having a thickness of 0.25 in. The number of test coupons corresponding to each ASTM standard test method is provided in Table 3.1. These coupons were tested in an INSTRON-SATEC Static Hydraulic Test Machine with a data acquisition system incorporating BlueHill 3 software. Brief descriptions of these tests are given below.

Table 3.1 - ASTM Coupons Tested

ASTM	Direction of Loading	Hole Diameter	Quantity
D638	0	NA	12
	90	NA	12
D3039	0	NA	12
	90	NA	12
D5766	0	0.25”	12
	90	0.25”	13
D5766	0	0.375”	12
	90	0.375”	13
D5766	0	0.50”	12
	90	0.50”	12
		Total	122

ASTM D638: A total of 24 Type 1 specimens, having the configuration shown in Figure 3.1 were tested in tension. Five specimens were discarded due to failure outside of the gage section. Results of individual test coupons are presented in Tables C.1 and C.2 of Appendix C and summarized in Table 3.2. Typical coupons failures are shown in Figure 3.2.

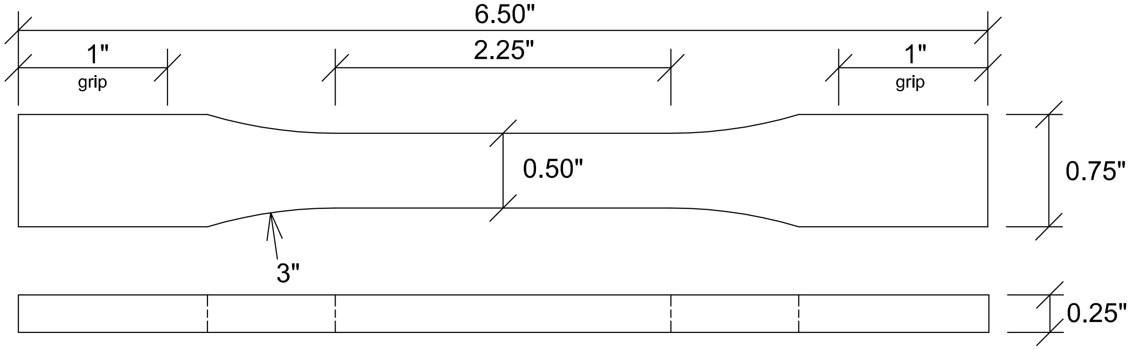


Figure 3.1 - ASTM D638 Dimensions

(a) Longitudinal **(b) Transverse**

Figure 3.2 - ASTM D638 Coupons after Failure

ASTM D3039: A total of 24 un-tabbed coupons having a rectangular prismatic shaped coupon shown in Figure 3.3 were tested in tension. Nine of these specimens were discarded due to failure at or near the grip regions. Results of individual test coupons are given in Tables C.3 and C.4 and summarized in Table 3.2. Typical coupon failure resulting from these tests are shown in Figure 3.4.

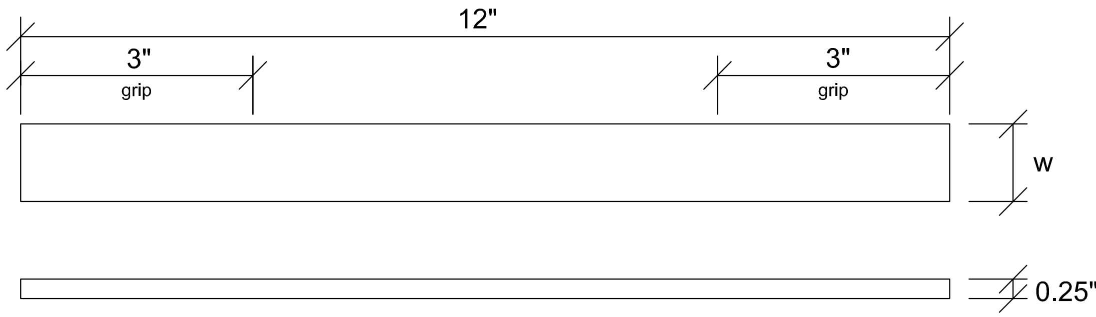
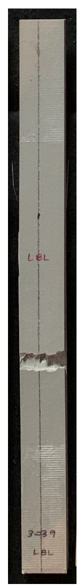


Figure 3.3 - ASTM D3039 Coupon Dimension



(a) Longitudinal

(b) Transverse

Figure 3.4 - ASTM 3039 Coupons after Failure

ASTM D5766: A total of 74 rectangular test specimens, with central holes having diameters of 0.25”, 0.375”, and 0.50” were tested. Coupon dimensions are shown in Figure 3.5. Results of these tests are given in Tables C.5 through C.10 and summarized in Table 3.2. Typical failure of coupons are shown in Figure 3.6.

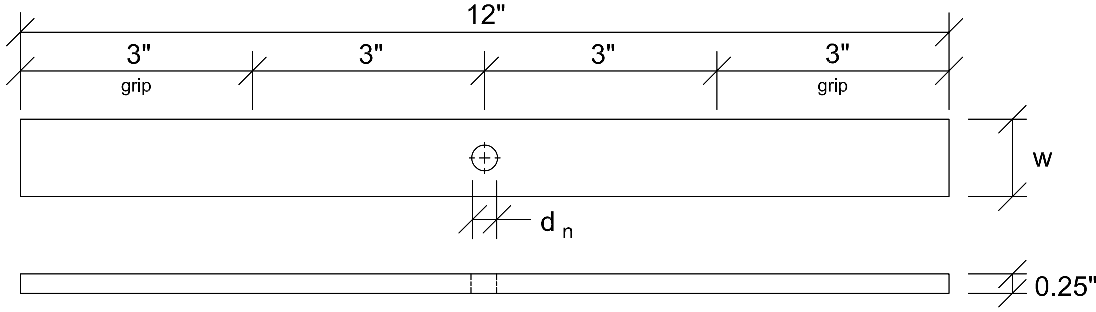
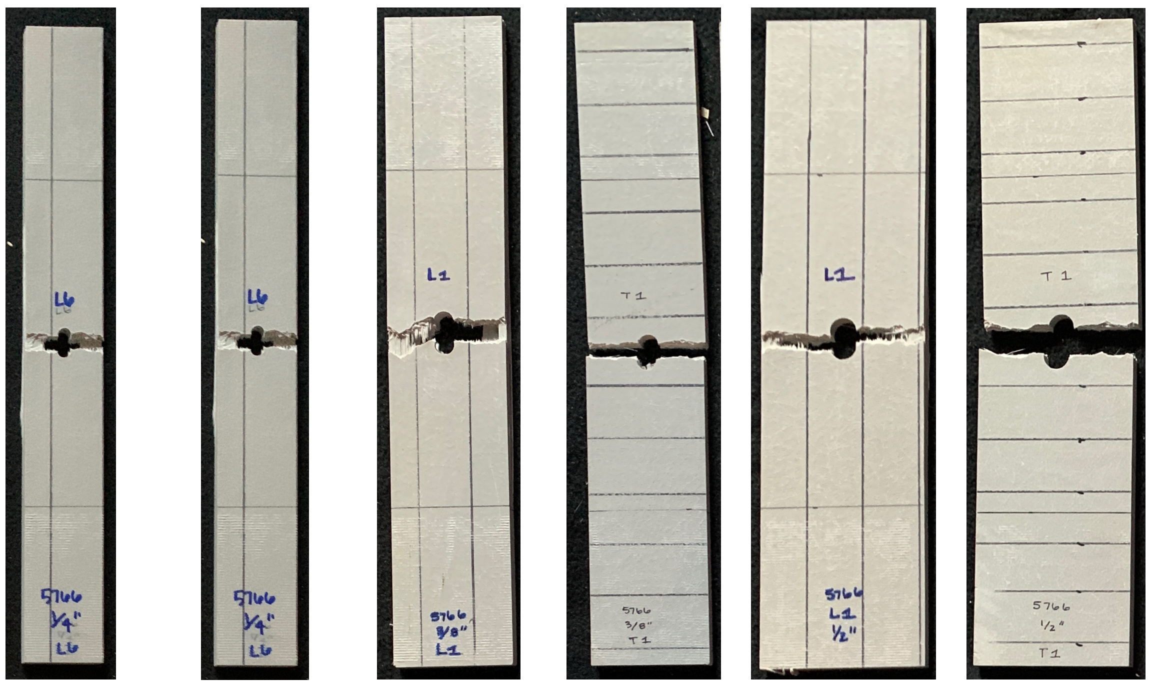


Figure 3.5 - ASTM D5766 Coupon Dimension



(a)	(b)	(c)	(d)	(e)	(f)
Longitudinal	**Transverse**	**Longitudinal**	**Transverse**	**Longitudinal**	**Transverse**
d=0.25”	**d=0.25”**	**d=0.375”**	**d=0.375”**	**d=0.50”**	**d=0.50”**

Figure 3.6 - ASTM D5766 Coupons after Failure

Table 3.2 - Summary of Coupon Test Results

Method		Fiber Orientation	Sample Size		F ksi
ASTM	D638	Longitudinal	7	Avg	24.2
				SD	6.9
				COV	0.29
		Transverse	12	Avg	12.3
				SD	0.8
				COV	0.07
	D3039	Longitudinal	7	Avg	30.8
				SD	0.9
				COV	0.03
		Transverse	8	Avg	11.9
				SD	0.3
				COV	0.03
	D5766 d=0.25”	Longitudinal	12	Avg	19.4
				SD	0.5
				COV	0.03
		Transverse	13	Avg	8.8
				SD	0.3
				COV	0.03
	D5766 d=0.375”	Longitudinal	12	Avg	18.6
				SD	1.0
				COV	0.05
		Transverse	12	Avg	8.1
				SD	0.3
				COV	0.04
	D5766 d=0.50”	Longitudinal	12	Avg	16.6
				SD	1.35
				COV	0.08
		Transverse	12	Avg	8.2
				SD	0.2
				COV	0.02

3.3 Tests on Single-Bolt Connections

A total of 32 single-bolt connections (Table 3.3) utilizing two bolts having diameters 0.25” and 0.5” were tested in tension. Test specimen dimensions, test set-up, and typical test specimen failures are shown in Figure 3.7, 3.8, and 3.9, respectively. All tests were performed in an INSTRON-SATEC Static Hydraulic Test Machine with a data acquisition system that incorporates BlueHill 3 software. In these tests, the rate of loading was 0.05 in/min. Of the 32 specimens tested, five specimens are discarded due to failure away from the hole in two cases, and testing malfunction in three cases. Results of these tests are presented in Tables D.1 - D.4 and summarized in Table 3.4.

Table 3.3 - Connection Samples

Bolt Diameter	Roving	Number of Tests
0.25”	Longitudinal	8
0.25”	Transverse	7
0.50”	Longitudinal	9
0.50”	Transverse	8
	Total	32

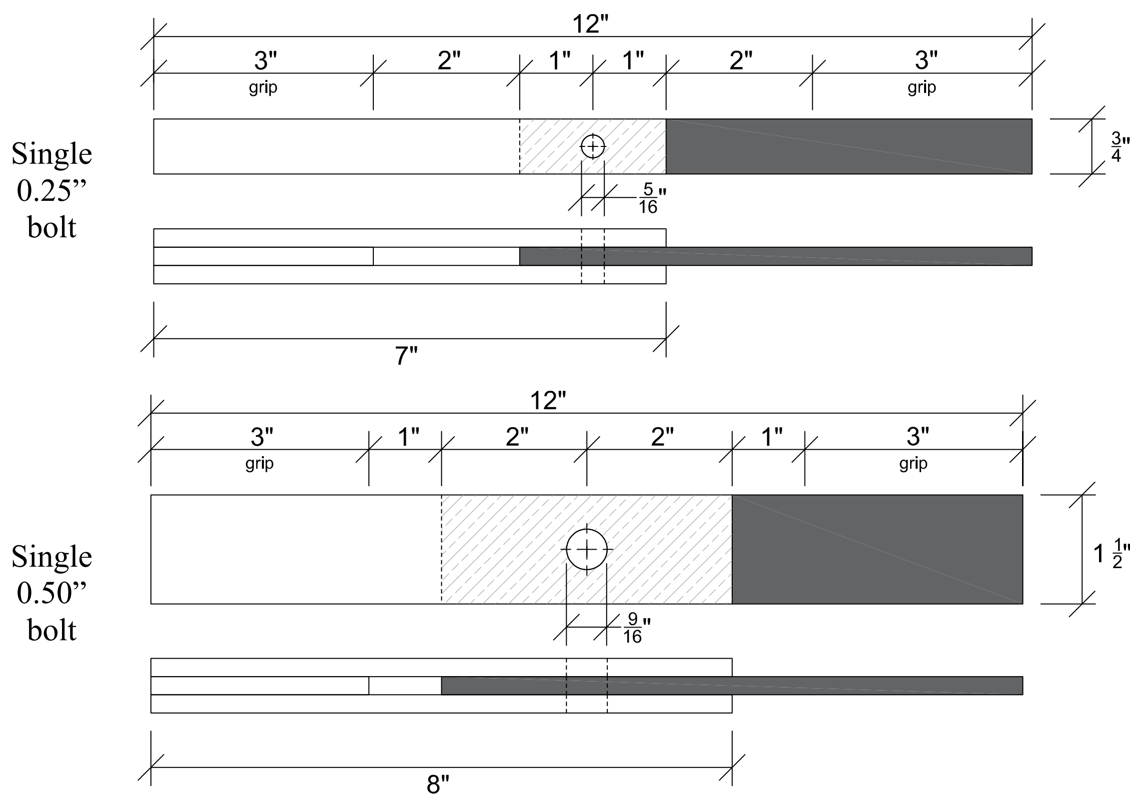


Figure 3.7 – Connection Specimen Dimensions

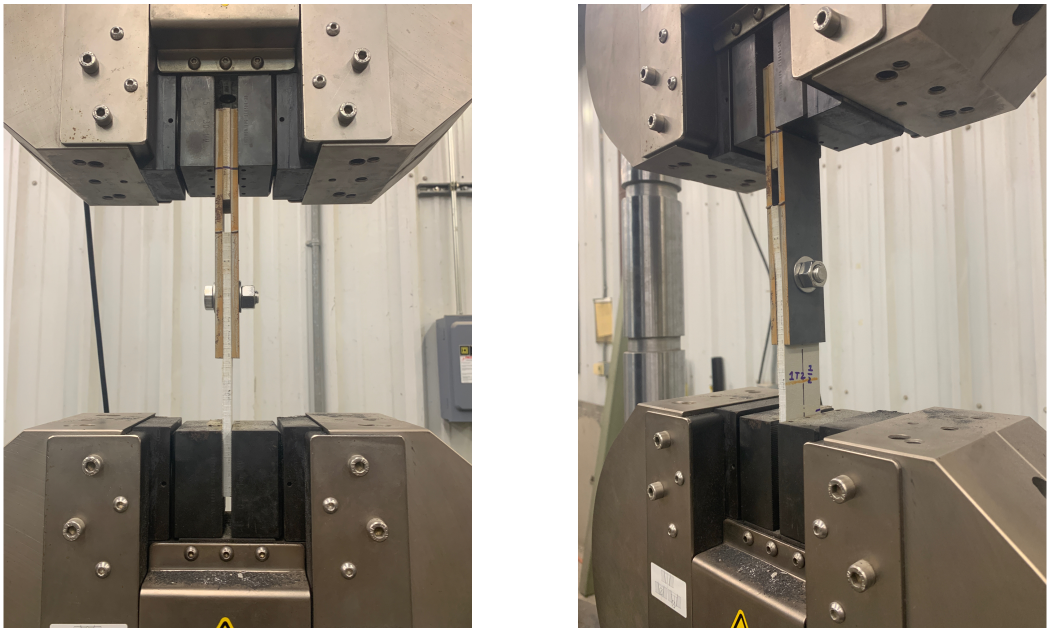
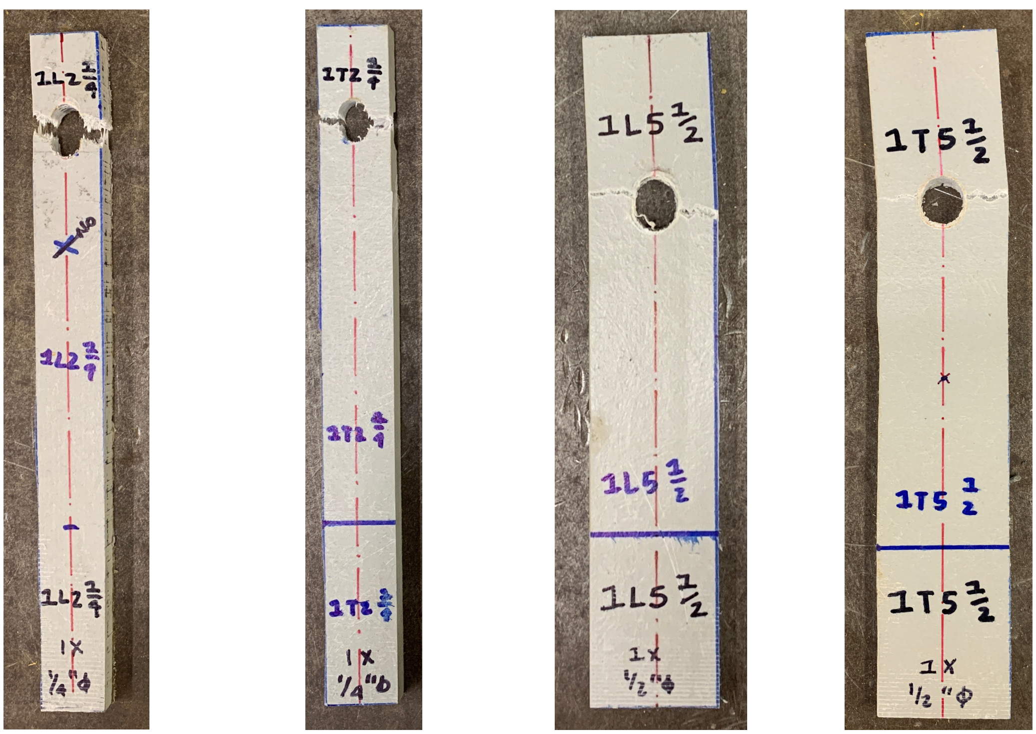


Figure 3.8 - Test Set-Up



(a) Longitudinal d=0.25" bolt	(b) Transverse d=0.25" bolt	(c) Longitudinal d=0.50" bolt	(d) Transverse d=0.50" bolt

Figure 3.9 - Typical Connection Failures

Table 3.4 - Connection Summary

Num. bolts	d	Fiber Orientation		F (ksi)
1	0.25”	Longitudinal	Avg	18
			SD	4
			COV	0.2
		Transverse	Avg	10
			SD	1
			COV	0.1
1	0.50”	Longitudinal	Avg	18
			SD	4
			COV	0.2
		Transverse	Avg	9
			SD	1
			COV	0.1

CHAPTER 4. ANALYSES AND DISCUSSION

This chapter presents the analyses of the experiments conducted to validate the simplified Equation 3.1 proposed to estimate the net-section tensile strength for single-bolted connections. In such an equation, A_n is the net area of the connection member and F^t is the material tensile strength that is determined in this chapter.

4.1 Analysis

The single-bolt tensile tests are assessed by both the Hart-Smith (1976) empirical method and Equation 3.1.

The Hart-Smith (1976) analysis method follows the methodology outlined in Chapter 2. The calculated values of P_{exp}/P_{calc} using the tensile strength determined from ASTM D3039 and D638 are show in Tables 4.1 – 4.4. The same information is shown graphically in Figures 4.1 – 4.4.

In addition, the values of P_{exp}/P_{calc} obtained from Equation 3.1, using the tensile strengths determined from ASTM D638, ASTM D3039, and ASTM D5766, are shown in Tables 4.5 and 4.6.

When applying data-curve fitting in the empirical method of Hart-Smith (1976) method to calculate the net-section tensile strength, it is concluded that:

1. The material tensile strength obtained from either ASTM D638 or D3039 will yield similar connection strength values. Tables 4.3 - 4.6 and Figures 4.1 - 4.4 illustrate this similarity.

2. Based on the results presented in Tables 4.3 - 4.6, the adoption of either the bolt hole diameter of bolt diameter when calculating the net section area will not influence the value of the connection tensile strength in a connection with a 1/16" bolt clearance.

Analysis results by means of Equation 3.1, where the material strength (F_{oh}^{t}) is determined from ASTM D5766, yields calculated strength values (P_{calc}) that correlate well with the experimental results (P_{exp}). Therefore, the proposed simplified approach of Equation 3.1~~,~~ for estimating the net-section tensile strength of single bolt connections~~,~~ is a viable replacement for the laborious existing approach proposed in the ASCE Pre-Standard (2010).

Table 4.1 - Analyses of Connection Experimental Tests Using D3039 Strength: Forces Applied in the Longitudinal Direction-0°

COUPON	$d = d_{bolt}$						$d = d_{hole}$					
	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$
1L1 1/4	1.50	3.20	0.23		2079	1.27	1.32	3.20	0.14		2092	1.26
1L2 1/4	1.70	3.21	0.32		2092	1.12	1.50	3.21	0.23		2107	1.11
1L4 1/4	1.88	3.14	0.41		1951	1.00	1.64	3.14	0.30	0.30	1948	1.00
1L5 1/4	2.27	3.17	0.58	0.41	1990	0.83	1.98	3.17	0.45		1995	0.83
1L6 1/4	2.19	3.13	0.56		1932	0.85	1.91	3.13	0.43		1926	0.86
1L8 1/4	1.75	3.16	0.35		1970	1.08	1.53	3.16	0.25		1971	1.08
	Nominal bolt diam. d_b = ¼”				Avg	1.02	Nominal bolt hole diam. $d_h = d_b$ +1/16"				Avg	1.02
					SD	0.17					SD	0.08
					COV	0.17					COV	0.08
1L1 1/2	1.79	5.91	0.16		4769	0.94	1.73	5.91	0.15		4759	0.95
1L2 1/2	1.47	5.93	0.10		4818	1.15	1.43	5.93	0.09		4808	1.15
1L3 1/2	1.83	5.82	0.17		4609	0.91	1.73	5.82	0.15		4463	0.94
1L4 1/2	1.62	5.81	0.13	0.14	4641	1.03	1.57	5.81	0.12	0.13	4635	1.03
1L5 1/2	1.56	5.97	0.11		4831	1.09	1.51	5.97	0.10		4829	1.09
1L6 1/2	1.91	5.80	0.19		4626	0.87	1.85	5.80	0.18		4615	0.88
1L7 1/2	1.73	5.87	0.15		4616	0.97	1.68	5.87	0.14		4623	0.97
1L8 1/2	1.62	5.91	0.13		4730	1.03	1.57	5.82	0.12		4700	1.04
	Nominal bolt diam. d_b = ½”				Avg	1.00	Nominal bolt hole diam. $d_h = d_b$ +1/16"				Avg	1.01
					SD	0.09					SD	0.09
					COV	0.09					COV	0.09

Table 4.2 - Analyses of Connection Experimental Tests Using D3039 Strength: Forces Applied in the Transverse Direction-90°

COUPON	$d = d_{bolt}$						$d = d_{hole}$					
	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{\exp}}{P_{cal}}$	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{\exp}}{P_{cal}}$
1T1 1/4	1.40	3.26	0.18	0.15	1126	0.95	1.24	3.26	0.11	0.08	1130	0.95
1T3 1/4	1.22	3.24	0.10		1146	1.09	1.08	3.24	0.03		1147	1.09
1T5 1/4	1.29	3.17	0.13		1123	1.03	1.14	3.17	0.06		1116	1.03
1T6 1/4	1.39	3.19	0.18		1128	0.96	1.21	3.19	0.10		1114	0.97
1T7 1/4	1.36	3.21	0.16		1132	0.98	1.20	3.21	0.09		1132	0.98
	Nominal bolt diam. $d_b = ¼$"				Avg	1.00	Nominal bolt hole diam. $d_h = d_b + 1/16$"				Avg	1.00
					SD	0.06					SD	0.06
					COV	0.06					COV	0.06
1T1 1/2	1.21	5.52	0.05	0.07	2051	1.09	1.16	5.52	0.04	0.07	1975	1.13
1T2 1/2	1.32	5.83	0.07		2286	1.01	1.28	5.83	0.06		2206	1.05
1T3 1/2	1.37	5.90	0.08		2287	0.98	1.33	5.90	0.07		2208	1.01
1T4 1/2	1.22	5.48	0.05		2090	1.08	1.18	5.48	0.04		2024	1.11
1T5 1/2	1.39	6.09	0.08		2369	0.98	1.37	6.09	0.07		2333	0.99
1T6 1/2	1.33	6.22	0.06		2412	1.03	1.29	6.22	0.06		23449	1.05
1T7 1/2	1.56	6.17	0.11		2441	0.87	1.52	6.17	0.10		2372	0.90
1T8 1/2	1.43	5.94	0.09		2256	0.94	1.39	5.94	0.08		2196	0.97
	Nominal bolt diam. $d_b = ½$"				Avg	1.00	Nominal bolt hole diam. $d_h = d_b + 1/16$"				Avg	1.03
					SD	0.07					SD	0.08
					COV	0.07					COV	0.08

Table 4.3 - Analyses of Connection Experimental Tests Using 638 Strength: Forces Applied in the Longitudinal Direction-0°

COUPON	$d = d_{bolt}$						$d = d_{hole}$					
	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$
1L1 1/4	1.18	3.20	0.08		2092	1.26	1.04	3.20	0.02		2122	1.24
1L2 1/4	1.34	3.21	0.15		2107	1.11	1.18	3.21	0.08		2137	1.09
1L4 1/4	1.48	3.14	0.22	0.22	1956	1.00	1.29	3.14	0.14		1966	0.99
1L5 1/4	1.78	3.17	0.36		1999	0.83	1.56	3.17	0.26	0.13	2017	0.82
1L6 1/4	1.72	3.13	0.34		1935	0.85	1.50	3.13	0.24		1941	0.85
1L8 1/4	1.37	3.16	0.17		1977	1.07	1.20	3.16	0.09		1991	1.07
	Nominal bolt hole diam. $d_h = d_b$ +1/16"				Avg	1.02	Nominal bolt hole diam. $d_h = d_b$ +1/16"				Avg	1.01
					SD	0.16					SD	0.16
					COV	0.16					COV	0.16
1L1 1/2	1.40	5.91	0.08		4703	0.96	1.36	5.91	0.07		4729	0.95
1L2 1/2	1.16	5.93	0.03		4753	1.16	1.12	5.93	0.02		4781	1.16
1L3 1/2	1.44	5.82	0.09		4533	0.93	1.35	5.82	0.07		4422	0.95
1L4 1/2	1.27	5.81	0.06		4563	1.05	1.24	5.81	0.05		4591	1.04
1L5 1/2	1.22	5.97	0.04	0.07	4773	1.10	1.19	5.97	0.04	0.06	4809	1.09
1L6 1/2	1.50	5.80	0.10		4546	0.89	1.45	5.80	0.09		4568	0.89
1L7 1/2	1.36	5.87	0.07		4546	0.99	1.32	5.87	0.07		4587	0.98
1L8 1/2	1.27	5.82	0.06		4651	1.05	1.23	5.82	0.05		4656	1.05
	Nominal bolt hole diam. $d_h = d_b$ +1/16"				Avg	1.02	Nominal bolt hole diam. $d_h = d_b$ +1/16"				Avg	1.01
					SD	0.09					SD	0.09
					COV	0.09					COV	0.09

Table 4.4 - Analyses of Connection Experimental Tests Using 638 Strength: Forces Applied in the Transverse Direction-90°

COUPON	$d = d_{bolt}$						$d = d_{hole}$					
	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$	k_{tc}	k_{te}	C	C_{des}	P_{cal} lbs	$\frac{P_{exp}}{P_{cal}}$
1T1 1/4	1.45	3.26	0.20		1126	0.95	1.28	3.26	0.13		1125	0.95
1T3 1/4	1.26	3.24	0.12		1147	1.09	1.11	3.24	0.05		1142	1.10
1T5 1/4	1.34	3.17	0.15	0.17	1124	1.03	1.18	3.17	0.08	0.10	1113	1.04
1T6 1/4	1.44	3.19	0.20		1129	0.95	1.26	3.19	0.12		1110	0.97
1T7 1/4	1.41	3.21	0.18		1133	0.98	1.24	3.21	0.11		1128	0.98
	Nominal bolt diam. d_b = ¼”				Avg SD COV	1.00 0.06 0.06	Nominal bolt hole diam. $d_h = d_b$ +1/16"				Avg SD COV	1.01 0.06 0.06
1T1 1/2	1.25	5.52	0.06		2050	1.09	1.20	5.52	0.04		2042	1.09
1T2 1/2	1.37	5.83	0.08		2280	1.01	1.32	5.83	0.07		2280	1.01
1T3 1/2	1.42	5.90	0.09		2281	0.98	1.37	5.90	0.08		2283	0.98
1T4 1/2	1.26	5.48	0.06	0.08	2089	1.08	1.22	5.48	0.05	0.07	2092	1.08
1T5 1/2	1.43	6.09	0.09		2361	0.98	1.41	6.09	0.08		2412	0.96
1T6 1/2	1.37	6.22	0.07		2402	1.03	1.34	6.22	0.06		2429	1.02
1T7 1/2	1.62	6.17	0.12		2431	0.87	1.57	6.17	0.11		2452	0.87
1T8 1/2	1.48	5.94	0.10		2250	0.94	1.44	5.94	0.09		2270	0.94
	Nominal bolt diam. d_b = ½”				Avg SD COV	1.00 0.07 0.07	Nominal bolt hole diam. $d_h = d_b$ +1/16"				Avg SD COV	0.99 0.07 0.07

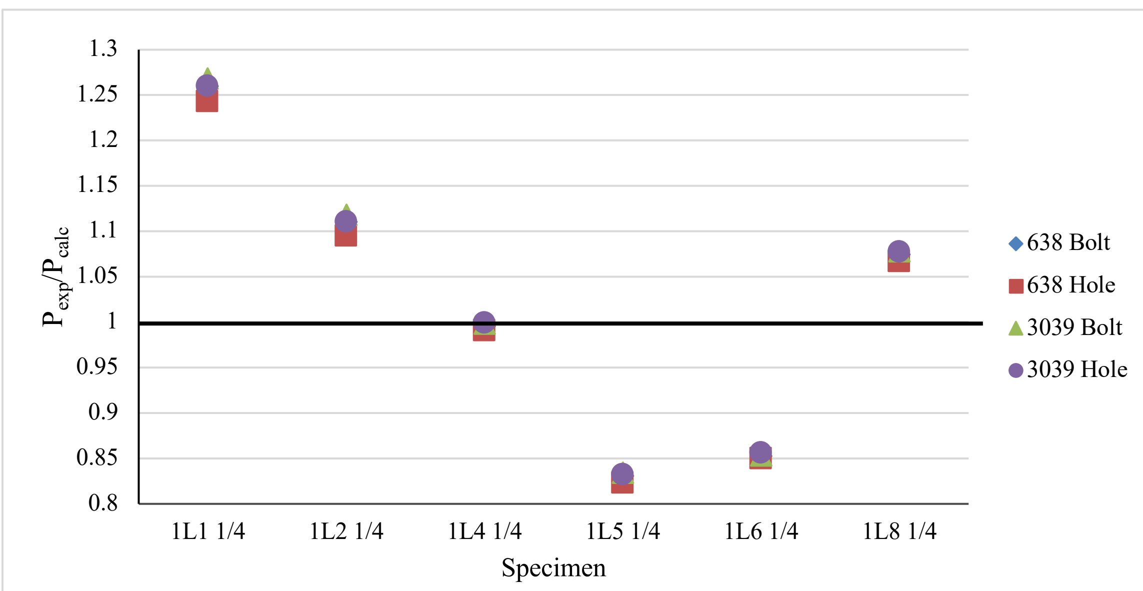


Figure 4.1 – P_{exp}/P_{calc} using Hart-Smith Method with Different Material Strengths: Force in Longitudinal Direction - ¼” Diameter Bolt

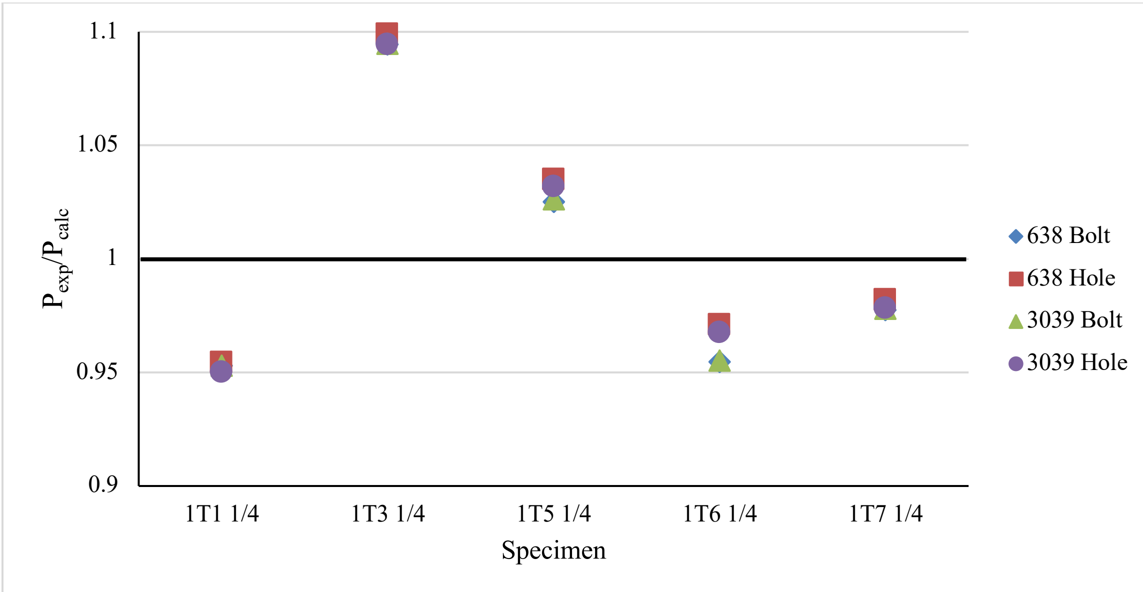


Figure 4.2 - P_{exp}/P_{calc} using Hart-Smith Method with Different Material Strengths: Force in Transverse Direction - ¼" Diameter Bolt

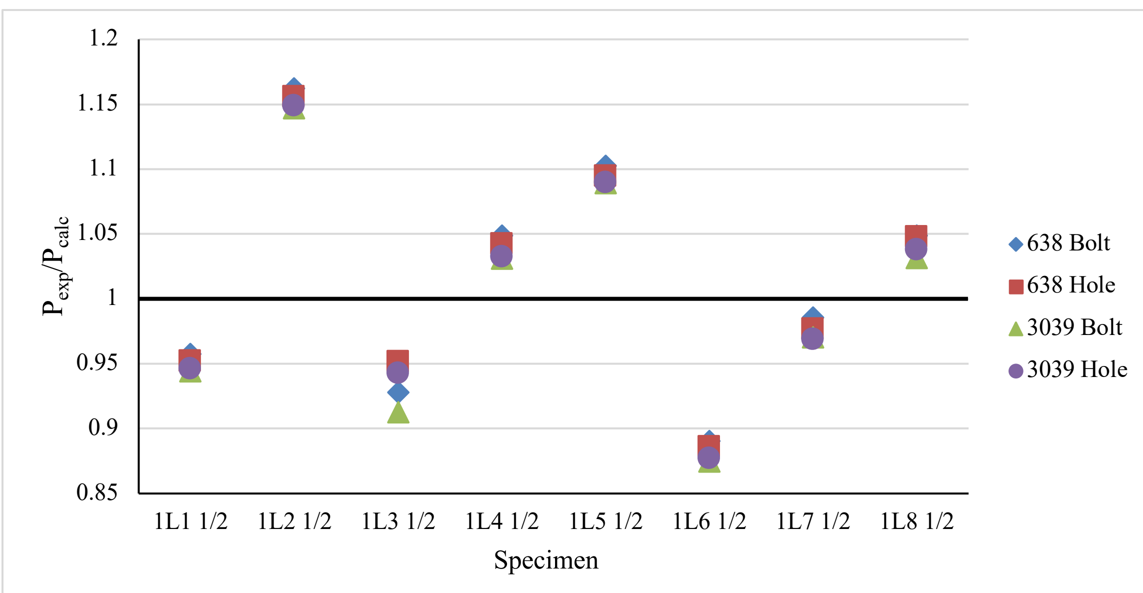


Figure 4.3 - P_{exp}/P_{calc} using Hart-Smith Method with Different Material Strengths: Force in Longitudinal Direction – ½" Diameter Bolt

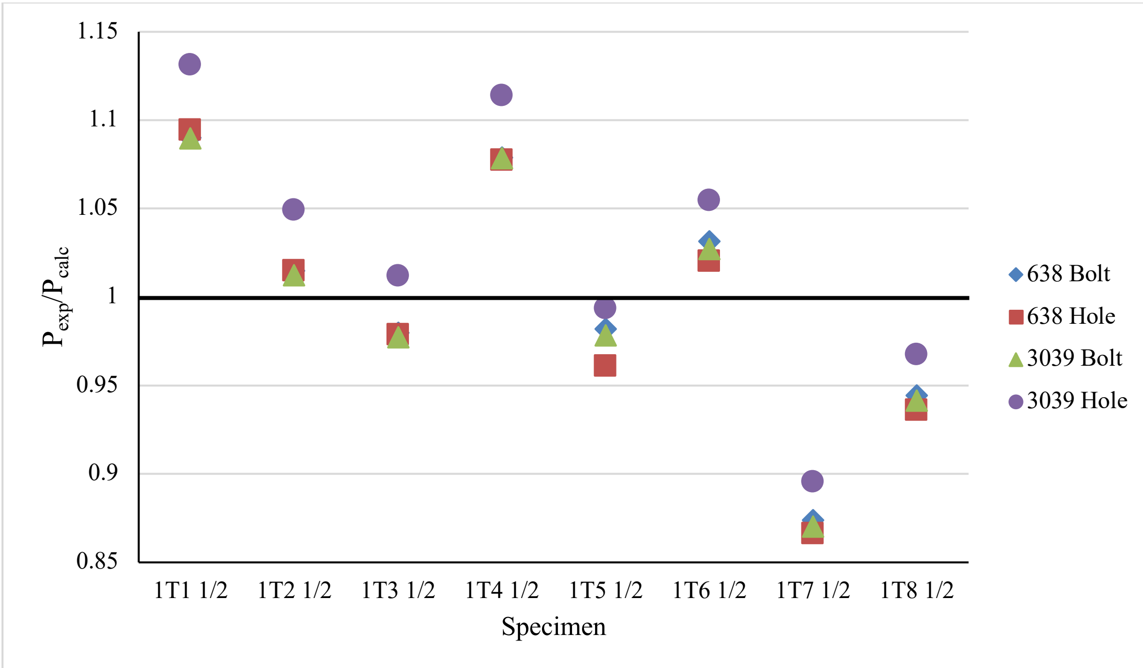


Figure 4.4 - P_{exp}/P_{calc} using Hart-Smith Method with Different Material Strengths: Force in Transverse Direction – ½" Diameter Bolt

Table 4.5 - Values of P_{exp}/P_{calc} using Equation 5.1: Force in Longitudinal Direction

COUPON	A in.^{2}	P_{exp} lb	D3039 F^t ksi	D3039 P_{calc} lb	D3039 P_{exp}/P_{calc}	D638 F^t ksi	D638 P_{calc} lb	D638 P_{exp}/P_{calc}	D5766 F^t ksi	D5766 P_{calc} lb	D5766 P_{exp}/P_{calc}
1L1 1/4	0.11	2635	30.83	3474.15	0.76	24.21	2728.16	0.97	19.43	2189.51	1.20
1L2 1/4	0.11	2340		3503.02	0.67		2750.83	0.85		2207.71	1.06
1L4 1/4	0.10	1947		3200.32	0.61		2513.13	0.77		2016.94	0.97
1L5 1/4	0.11	1660		3293.53	0.50		2586.33	0.64		2075.68	0.80
1L6 1/4	0.10	1649		3156.47	0.52		2478.69	0.67		1989.30	0.83
1L8 1/4	0.11	2124		3246.62	0.65		2549.49	0.83		2046.12	1.04
				Avg	0.62		Avg	0.79		Avg	0.98
				SD	0.10		SD	0.12		SD	0.15
				COV	0.16		COV	0.15		COV	0.15
1L1 1/2	0.25	4504	30.83	7797.47	0.58	24.21	6123.15	0.74	16.64	4208.56	1.07
1L2 1/2	0.26	5526		7887.89	0.70		6194.16	0.89		4257.37	1.30
1L3 1/2	0.24	4208		7259.68	0.58		5700.84	0.74		3918.30	1.07
1L4 1/2	0.24	4785		7534.85	0.64		5916.92	0.81		4066.82	1.18
1L5 1/2	0.26	5264		7949.80	0.66		6242.78	0.84		4290.78	1.23
1L6 1/2	0.24	4048		7491.57	0.54		5882.93	0.69		4043.45	1.00
1L7 1/2	0.24	4480		7546.79	0.59		5926.30	0.76		4073.26	1.10
1L8 1/2	0.25	4879		7642.93	0.64		6001.80	0.81		4125.15	1.18
				Avg	0.62		Avg	0.78		Avg	1.14
				SD	0.05		SD	0.07		SD	0.10
				COV	0.08		COV	0.09		COV	0.09

Note:
A = net cross section area of connection coupon
P = load at failure
F^t = material tensile strength

Table 4.6 - Values of P_{exp}/P_{calc} using Equation 5.1: Force in Transverse Direction

COUPON	A in.^{2}	P_{exp} lb	D3039 F^t ksi	D3039 P_{calc} lb	D3039 $\frac{P_{exp}}{P_{calc}}$	D638 F^t ksi	D638 P_{calc} lb	D638 $\frac{P_{exp}}{P_{calc}}$	D5766 F^t ksi	D5766 P_{calc} lb	D5766 $\frac{P_{exp}}{P_{calc}}$
1T1 1/4	0.11	1073	11.85	1333.99	0.80	12.25	1379.02	0.78	8.80	990.64	1.08
1T3 1/4	0.11	1255		1351.97	0.93		1397.61	0.90		1004.00	1.25
1T5 1/4	0.11	1152		1310.69	0.88		1354.93	0.85		973.34	1.18
1T6 1/4	0.11	1078		1308.83	0.82		1353.01	0.80		971.96	1.11
1T7 1/4	0.11	1107		1332.21	0.83		1377.18	0.80		989.32	1.12
				Avg	0.85		Avg	0.83		Avg	1.15
				SD	0.05		SD	0.05		SD	0.07
				COV	0.06		COV	0.06		COV	0.06
1T1 1/2	0.22	2235	11.85	2600.19	0.86	12.25	2687.96	0.83	8.15	1788.32	1.25
1T2 1/2	0.25	2314		2951.84	0.78		3051.48	0.76		2030.17	1.14
1T3 1/2	0.25	2235		2965.01	0.75		3065.10	0.73		2039.23	1.10
1T4 1/2	0.22	2254		2659.04	0.85		2748.80	0.82		1828.79	1.23
1T5 1/2	0.27	2318		3164.19	0.73		3271.00	0.71		2176.21	1.07
1T6 1/2	0.27	2478		3207.72	0.77		3316.00	0.75		2206.15	1.12
1T7 1/2	0.27	2125		3231.11	0.66		3340.18	0.64		2222.24	0.96
1T8 1/2	0.25	2125		2955.06	0.72		3054.81	0.70		2032.39	1.05
				Avg	0.77		Avg	0.74		Avg	1.11
				SD	0.07		SD	0.06		SD	0.10
				COV	0.09		COV	0.08		COV	0.09

Note:
A = net cross section area of connection coupon
P = load at failure
F^t = material tensile strength

CHAPTER 5. CONCLUSION

Based on the results reported in this study, it is concluded that:

1. When computing a single-bolt tensile rupture strength in a pultruded plate, according to Hart-Smith's empirical approach, the area of the net section associated with tensile rupture failure mode can be calculated as the gross area minus either the area of the bolt or the area of the bolt hole as long as bolt clearances are 1/16”.
2. Based on the single-bolt connection tests conducted and reported in this thesis, the net-section tensile strengths calculated from Equation 3.1 with the material tensile strength determined from ASTM D5766, yields values correlates very closely with those obtained experientially, and is therefore an appropriate method to estimate the net-section tensile strength of a single-bolted connection.

5.1 Recommendation for Future Studies

As Equation 3.1 was developed to be a simplified approach to estimate the net-section tensile strength in single-bolt connections for pultruded plates (Figure 1.1a), it is recommended that additional experiments be conducted to examine the validity of the approach presented in this work for multi-row bolted connections such as those shown in Figure 1.1b-i.

APPENDIX A. ASCE PRE-STANDARD

A.1 Calculation Example using the ASCE Pre-Standard

Appendix A presents a single-bolt, pultruded plate connection example using the ASCE Pre-Standard (2010) to compute the net-tensile strength of each connection.

A.3.1 Example

This example provides the steps to calculate the net rupture tensile strength of a single, ¼" bolt plate connection, with a roving angle of 2°, as shown in Figure A.1. and Table A.1.

Table A.1 - Single Bolt Connection Properties

Variable	Value	
F_L^t	25,000	psi
F_T^t	8,000	psi
d	0.25	in
d_n	0.3125	in
e_1	1.50	in
e_2	0.50	in
t	0.25	in
θ	2	°

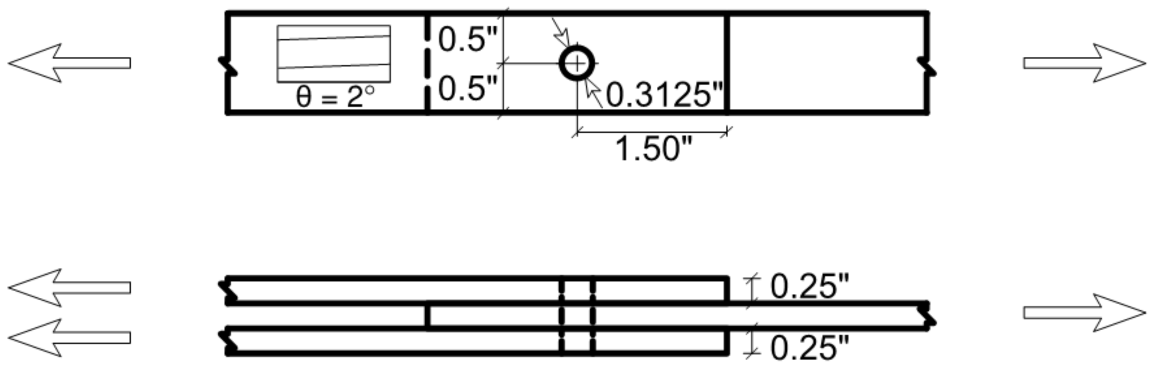


Figure A.1 – Connection Detail

Step 1: In the single-bolt schematic, n=1; therefore, Section 8.3.2.4 in the ASCE Pre-Standard (2010) is applicable. Given $\theta = 2° < 5°$, this connection has a longitudinal fiber orientation.

Step 2: Calculate the effective width of the plate as outlined in Equation 1.3.

$$w = e_2 + e_2 = 0.5" + 0.5" = 1.0"$$

Step 3: Calculate the geometric reduction coefficient as outlined in Equation 1.6**.**

$$\frac{e_1}{w} = \frac{1.5"}{1.0"} = 1.5 > 1 \ \rightarrow \Theta = 1$$

Step 4: With $S_{pr} = \frac{w}{d} = \frac{1.0"}{0.25"} = 4$ and $C_L = 0.4$, the net tension stress concentration factor (Equation 1.14) is:

$$K_{nt,L} = C_L \left[S_{pr} - 1.5 \, \frac{S_{pr} - 1}{S_{pr} + 1} \Theta \right] + 1 = 0.4 \left[4 - 1.5 \frac{(4-1)}{(4+1)} 1 \right] + 1 = 2.24$$

Step 5*:* Given the roving angle of 2°, the tensile strength characteristic value and the net tensile rupture strength of the connection (Equation 1.8, 1.1, and 1.2) is:

$$F^t{}_i = F^t{}_L = 25{,}000\ psi$$

$$R_{nt} = \frac{tF^t{}_L}{K_{nt,L}}[w - nd_n] = \frac{0.25" \times 25{,}000 psi}{2.24}[1.0" - 1 \times 0.3125"] = 1{,}918\ lb$$

$$\phi = 0.5$$

$$\phi R_{nt} = 0.5 \times 1{,}918\ lb = 959\ lb$$

APPENDIX B. ROSNER TESTING DATA

Table B.1 - Rosner Experimental Test Values

Coupon	Roving	t in.	w in.	d in.	e in.	A in.^{2}	F_{tu} psi	P_{exp} lb.
A1	0	0.38	1.00	0.81	0.75	0.14	28700	2750
A2	0	0.38	1.00	0.81	8.00	0.14	28700	3250
A3	0	0.38	1.50	0.81	1.50	0.52	28700	9900
A4	0	0.38	1.50	0.81	2.50	0.52	28700	9850
A5	0	0.38	1.50	0.81	4.00	0.52	28700	8850
A6	0	0.38	2.00	0.81	1.50	0.89	28700	12425
A7	0	0.38	2.00	0.81	2.50	0.89	28700	12990
A8	0	0.38	2.00	0.81	4.00	0.89	28700	13775
B1	0	0.50	1.00	0.81	0.75	0.19	24100	3000
B2	0	0.50	1.00	0.81	8.00	0.19	24100	3350
B3	0	0.50	1.50	0.81	1.50	0.69	24100	11750
B4	0	0.50	1.50	0.81	2.50	0.69	24100	13600
B5	0	0.50	1.50	0.81	4.00	0.69	24100	12350
B6	0	0.50	2.00	0.81	1.50	1.19	24100	16400
B7	0	0.50	2.00	0.81	2.50	1.19	24100	16950
B8	0	0.50	2.00	0.81	4.00	1.19	24100	18750
C1	90	0.50	1.00	0.81	0.75	0.19	16000	2650
C2	90	0.50	1.00	0.81	8.00	0.19	16000	2630
C3	90	0.50	1.50	0.81	1.50	0.69	16000	7840
C4	90	0.50	1.50	0.81	2.50	0.69	16000	6450
C5	90	0.50	1.50	0.81	4.00	0.69	16000	7210
C6	90	0.50	2.00	0.81	1.50	1.19	16000	12990
C7	90	0.50	2.00	0.81	2.50	1.19	16000	11500
C8	90	0.50	2.00	0.81	4.00	1.19	16000	13690
D1	45	0.50	1.00	0.81	0.75	0.19	17000	2570
D2	45	0.50	1.00	0.81	8.00	0.19	17000	2600
D3	45	0.50	1.50	0.81	1.50	0.69	17000	9040
D4	45	0.50	1.50	0.81	2.50	0.69	17000	6975
D5	45	0.50	1.50	0.81	4.00	0.69	17000	9750
D6	45	0.50	2.00	0.81	1.50	1.19	17000	14590
D7	45	0.50	2.00	0.81	2.50	1.19	17000	10750
D8	45	0.50	2.00	0.81	4.00	1.19	17000	14390
E1	0	0.75	1.00	0.81	0.75	0.28	24100	4580
E2	0	0.75	1.00	0.81	8.00	0.28	24100	5270
E3	0	0.75	1.50	0.81	1.50	1.03	24100	17240
E4	0	0.75	1.50	0.81	2.50	1.03	24100	18870
E5	0	0.75	1.50	0.81	4.00	1.03	24100	18890
E6	0	0.75	2.00	0.81	1.50	1.78	24100	23830
E7	0	0.75	2.00	0.81	2.50	1.78	24100	26330
E8	0	0.75	2.00	0.81	4.00	1.78	24100	29150

APPENDIX C. MATERIAL TENSILE STRENGTH TESTING RESULTS

Table C.1 - Material Properties via ASTM D638 Longitudinal Results

Coupon	w in.	t in.	A_e in.^{2}	P psi	F lb.
L2	0.509	0.251	0.13	2355	18.4
L4	0.510	0.252	0.13	2250	17.5
L7	0.516	0.255	0.13	3000	22.9
L8	0.516	0.254	0.13	3650	27.8
L9	0.516	0.254	0.13	4200	32.1
L11	0.517	0.255	0.13	4400	33.3
L12	0.511	0.252	0.13	2250	17.4
Average	0.51	0.25	0.13	3157.92	24.21
SD	0.00	0.00	0.00	929.91	6.88
COV	0.00	0.00	0.00	0.29	0.28
Specimens L1, L3, L5, L6, and L10 were discarded as a result of failure outside of the narrow section					

Table C.2 - Material Properties via ASTM D638 Transverse Results

Coupon	w in.	t in.	A_e in.^{2}	P psi	F lb.
T1	0.511	0.261	0.13	1830	13.7
T2	0.517	0.259	0.13	1640	12.3
T3	0.518	0.260	0.13	1850	13.7
T4	0.517	0.259	0.13	1570	11.7
T5	0.519	0.258	0.13	1650	12.3
T6	0.518	0.258	0.13	1600	12.0
T7	0.518	0.261	0.14	1700	12.6
T8	0.518	0.261	0.14	1580	11.7
T9	0.518	0.259	0.13	1650	12.3
T10	0.517	0.257	0.13	1520	11.4
T11	0.518	0.261	0.14	1680	12.4
T12	0.518	0.257	0.13	1450	10.9
Average	0.52	0.26	0.13	1643.33	12.25
SD	0.00	0.00	0.00	115.23	0.84
COV	0.00	0.00	0.00	0.07	0.07

Table C.3 - Coupon Longitudinal Tensile Strength Results per ASTM D3039

Coupon	w in.	t in.	A_e in.^{2}	P psi	F lb.
L4	1.016	0.257	0.26	7700	29.4
L5	1.013	0.260	0.26	8300	31.5
L6	1.015	0.260	0.26	8250	31.3
L8	1.016	0.258	0.26	7775	29.7
L9	1.016	0.259	0.26	8275	31.5
L11	1.016	0.257	0.26	8166	31.2
L12	1.014	0.259	0.26	8200	31.2
Average	1.02	0.26	0.26	8095.14	30.83
SD	0.00	0.00	0.00	249.31	0.88
COV	0.00	0.00	0.00	0.03	0.03
Specimens L1, L2, L3, L7, and L10 were discarded due to failure at or near grip regions.					

Table C.4 - Coupon Transverse Tensile Strength Results per ASTM D3039

Coupon	w in.	t in.	A_e in.^{2}	P psi	F lb.
T1	1.013	0.260	0.26	3100	11.8
T6	1.013	0.260	0.26	3150	12.0
T7	1.013	0.260	0.26	3150	11.9
T8	1.019	0.260	0.26	3100	11.7
T9	1.013	0.259	0.26	3250	12.4
T10	1.015	0.261	0.26	3100	11.7
T11	1.017	0.260	0.26	3100	11.7
T12	1.017	0.261	0.26	3050	11.5
Average	1.02	0.26	0.26	3128.57	11.85
SD	0.00	0.00	0.00	63.62	0.28
COV	0.00	0.00	0.00	0.02	0.02
Specimens T2, T3, T4, and T5 were discarded due to failure at or near grip regions.					

Table C.5 - Coupon Longitudinal Tensile Strength Results per ASTM D5766, d=0.25”

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P psi	F lb.
T1	1.515	0.265	0.256	0.33	8000	24.0
T2	1.512	0.260	0.246	0.33	7800	23.7
T3	1.510	0.265	0.248	0.33	8000	23.9
T4	1.511	0.261	0.248	0.33	7500	22.8
T5	1.513	0.261	0.245	0.33	7800	23.6
T6	1.513	0.261	0.249	0.33	7600	23.0
T7	1.511	0.263	0.249	0.33	7900	23.8
T8	1.513	0.262	0.251	0.33	7500	22.7
T9	1.512	0.263	0.245	0.33	7900	23.7
T10	1.513	0.264	0.247	0.33	7500	22.4
T11	1.511	0.263	0.248	0.33	7300	22.0
T12	1.514	0.260	0.250	0.33	7700	23.5
Average	1.51	0.26	0.25	0.33	7708	23.25
SD	0.00	0.00	0.00	0.00	227.47	0.65
COV	0.00	0.00	0.00	0.00	0.03	0.03

Table C.6 - Coupon Transverse Tensile Strength Results per ASTM D5766, d=0.25”

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P psi	F lb.
T1	1.512	0.259	0.248	0.33	3200	9.8
T2	1.511	0.252	0.251	0.32	3500	11.0
T3	1.509	0.259	0.243	0.33	3300	10.1
T4	1.507	0.259	0.247	0.33	3400	10.4
T5	1.503	0.253	0.248	0.32	3500	11.0
T6	1.510	0.258	0.250	0.33	3500	10.8
T7	1.510	0.259	0.248	0.33	3300	10.1
T8	1.512	0.251	0.236	0.32	3500	10.9
T9	1.512	0.258	0.247	0.33	3500	10.7
T10	1.514	0.252	0.246	0.32	3300	10.3
T11	1.510	0.253	0.239	0.32	3300	10.3
T12	1.510	0.251	0.230	0.32	3300	10.3
Average	1.510	0.258	0.248	0.33	3300	10.1
SD	1.51	0.26	0.24	0.32	3392	10.50
COV	1.00	1.01	0.96	0.97	1.03	1.04

Table C.7 - Coupon Longitudinal Tensile Strength Results per ASTM D5766, d=0.375”

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P psi	F lb.
T1	2.263	0.263	0.364	0.50	11000	22.0
T2	2.260	0.264	0.363	0.50	11700	23.4
T3	2.262	0.260	0.360	0.49	11800	23.9
T4	2.262	0.262	0.367	0.50	11200	22.5
T5	2.262	0.262	0.375	0.49	11100	22.4
T6	2.262	0.261	0.371	0.49	10600	21.5
T7	2.261	0.258	0.366	0.49	10400	21.3
T8	2.261	0.259	0.359	0.49	10300	20.9
T9	2.261	0.261	0.375	0.49	11500	23.4
T10	2.263	0.259	0.372	0.49	11600	23.7
T11	2.259	0.260	0.372	0.49	9900	20.2
T12	2.258	0.258	0.372	0.49	10300	21.1
Average	2.26	0.26	0.37	0.49	10950	22.19
SD	0.00	0.00	0.01	0.00	637.47	1.22
COV	0.00	0.00	0.00	0.84	0.06	0.05

Table C.8 - Coupon Transverse Tensile Strength Results per ASTM D5766, d=0.375”

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P psi	F lb.
T1	2.264	0.251	0.372	0.47	4700	9.9
T2	2.258	0.250	0.358	0.48	4600	9.7
T3	2.261	0.253	0.370	0.48	4500	9.4
T4	2.260	0.252	0.265	0.50	4550	9.0
T5	2.252	0.253	0.373	0.48	4600	9.7
T6	2.252	0.250	0.373	0.47	4500	9.6
T7	2.254	0.253	0.376	0.47	4400	9.3
T8	2.264	0.251	0.375	0.47	4600	9.7
T9	2.252	0.251	0.379	0.47	4750	10.1
T10	2.254	0.254	0.375	0.48	4950	10.4
T11	2.263	0.259	0.374	0.49	4800	9.8
T12	2.261	0.251	0.380	0.47	4650	9.8
Average	2.26	0.25	0.36	0.48	4638	9.71
SD	0.00	0.00	0.03	0.01	152.44	0.37
COV	0.00	0.00	0.08	0.02	0.03	0.04

Table C.9 - Coupon Longitudinal Tensile Strength Results per ASTM D5766, d=0.50"

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P psi	F lb.
T1	3.015	0.255	0.470	0.65	12000	18.5
T2	3.010	0.257	0.473	0.65	12300	18.9
T3	3.014	0.259	0.478	0.66	13500	20.5
T4	3.013	0.261	0.486	0.66	13500	20.5
T5	3.013	0.260	0.484	0.66	12500	19.0
T6	3.010	0.251	0.484	0.63	12800	20.2
T7	3.013	0.248	0.480	0.63	9800	15.6
T8	3.014	0.258	0.484	0.65	13300	20.3
T9	3.012	0.247	0.481	0.62	13000	20.8
T10	3.011	0.251	0.488	0.63	13300	21.0
T11	3.015	0.253	0.480	0.64	13800	21.5
T12	3.014	0.256	0.485	0.65	13500	20.8
Average	3.01	0.25	0.48	0.65	12775	19.80
SD	0.00	0.00	0.01	0.01	1086.38	1.62
COV	0.00	0.00	0.21	0.02	0.09	0.08

Table C.10 - Coupon Transverse Tensile Strength Results per ASTM D5766, d=0.50"

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P psi	F lb.
T1	2.996	0.254	0.464	0.64	5800	9.0
T2	2.990	0.238	0.471	0.60	5800	9.7
T3	2.993	0.236	0.472	0.60	6000	10.1
T4	2.995	0.236	0.475	0.59	5600	9.4
T5	2.995	0.236	0.478	0.60	5900	9.9
T6	2.997	0.246	0.465	0.62	6100	9.8
T7	2.995	0.247	0.247	0.68	6000	8.8
T8	3.000	0.247	0.438	0.63	5900	9.3
T9	2.997	0.247	0.475	0.62	6000	9.6
T10	2.997	0.247	0.471	0.62	6100	9.8
T11	2.993	0.236	0.477	0.59	5800	9.8
T12	2.976	0.245	0.473	0.61	6100	9.9
Average	2.99	0.24	0.45	0.62	5925	9.60
SD	0.01	0.01	0.06	0.03	154.48	0.37
COV	0.00	0.42	0.13	0.05	0.03	0.04

APPENDIX D. SINGLE-BOLT CONNECTION TEST RESULTS

Table D.1 - Single ¼" Bolt Connection Longitudinal Results

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P lb.	F ksi
1L1 1/4	0.735	0.264	0.309	0.11	2635	23.39
1L2 1/4	0.737	0.266	0.309	0.11	2340	20.59
1L4 1/4	0.716	0.255	0.309	0.10	1947	18.76
1L5 1/4	0.725	0.257	0.309	0.11	1660	15.54
1L6 1/4	0.712	0.254	0.309	0.10	1649	16.10
1L8 1/4	0.721	0.256	0.309	0.11	2124	20.17
Average	0.72	0.26	0.31	0.11	2059	19.09
SD	0.01	0.01	0.00	0.00	388.68	2.95
COV	0.01	0.04	0.00	0.00	0.19	0.15
Specimen 1L3 ¼ was discarded as a result of testing machine malfunction Specimen 1L7 ¼ was discarded as a result of failure away from the hole						

Table D.2 - Single ¼" Bolt Connection Transverse Results

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P lb.	F ksi
1T1 1/4	0.753	0.253	0.308	0.11	1073	9.54
1T3 1/4	0.746	0.261	0.308	0.11	1255	11.00
1T5 1/4	0.727	0.264	0.307	0.11	1152	10.42
1T6 1/4	0.732	0.263	0.311	0.11	1078	9.76
1T7 1/4	0.738	0.261	0.307	0.11	1107	9.85
Average	0.74	0.26	0.31	0.11	1133	10.11
SD	0.01	0.00	0.00	0.00	75.08	0.59
COV	0.01	0.00	0.00	0.00	0.07	0.06
Specimens 1T2 ¼ and 1T4 ¼ were discarded as a result of testing machine malfunction						

Table D.3 - Single ½" Bolt Connection Longitudinal Results

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P lb.	F ksi
1L1 1/2	1.496	0.262	0.531	0.25	4504	17.81
1L2 1/2	1.499	0.264	0.531	0.26	5526	21.60
1L3 1/2	1.471	0.258	0.558	0.24	4208	17.87
1L4 1/2	1.469	0.260	0.529	0.24	4785	19.58
1L5 1/2	1.511	0.263	0.530	0.26	5264	20.41
1L6 1/2	1.465	0.260	0.530	0.24	4048	16.66
1L7 1/2	1.483	0.256	0.527	0.24	4480	18.30
1L8 1/2	1.470	0.265	0.534	0.25	4879	19.68
Average	0.74	1.48	0.26	0.53	0.25	4712
SD	0.01	0.02	0.00	0.01	0.01	506.10
COV	0.01	0.01	0.00	0.02	0.04	0.11
Specimen 1L9 ½ was discarded as a result of failure away from the hole						

Table D.4 - Single ½" Bolt Connection Transverse Results

Coupon	w in.	t in.	d_n in.	A_e in.^{2}	P lb.	F ksi
1T1 1/2	1.391	0.256	0.533	0.22	2235	10.19
1T2 1/2	1.474	0.265	0.534	0.25	2314	9.29
1T3 1/2	1.491	0.261	0.534	0.25	2235	8.93
1T4 1/2	1.381	0.263	0.528	0.22	2254	10.05
1T5 1/2	1.543	0.260	0.516	0.27	2318	8.68
1T6 1/2	1.577	0.258	0.528	0.27	2478	9.15
1T7 1/2	1.564	0.264	0.530	0.27	2125	7.79
1T8 1/2	1.503	0.255	0.527	0.25	2125	8.52
Average	1.49	0.26	0.53	0.25	2260	9.07
SD	0.07	0.00	0.01	0.02	114.39	0.79
COV	0.05	0.00	0.02	0.08	0.05	0.09

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